THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Some Aspects on Contamination Control in Hospitals

Observations and Measurements

CATINKA ULLMANN

Department of Architecture and Civil Engineering
Building Services Engineering
CHALMERS UNIVERISTY OF TECHNOLOGY
Gothenburg, Sweden 2019

Some Aspects on Contamination Control in Hospitals
Observations and Measurements
CATINKA ULLMANN

ISBN 978-91-7905-138-9
Doktorsavhandlingar vid Chalmers tekniska högskola. Ny serie nr 4605 (ISSN 0346-718X)

Department of Architecture and Civil Engineering,
Division of Building Services Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover: Operating room. Photo Catinka Ullmann

Printed by Chalmers digitaltryck
Gothenburg, Sweden 2019

Some Aspects on Contamination Control in Hospitals

Observations and Measurements

C. ULLMANN

Division of Building Services Engineering
Department of Architecture and Civil Engineering
Chalmers University of Technology

ABSTRACT

The thesis describes an engineering approach to airborne contamination risks in different environments of Swedish hospitals and the purpose is to increase the understanding and awareness of these risks.

Autoclaves are common process equipment in sterile supply centers. During unloading of autoclaves, temperature differences cause entrainment of room air into the autoclave chamber with its sterile packages, and contamination risks occur. To increase the understanding of air movements through the autoclave opening, measurements and CFD simulations have been performed. Results show that UDF-unit with HEPA-filter close to the opening of the autoclave reduces the risk of contamination.

Functional clothing systems reduce the number of airborne bacteria-carrying particles from the staff in the operating room. Measurements show that the microbial source strength varies among clothing systems. The number of people present, their activity level, and type of clothing systems affect the microbiological air cleanliness during ongoing surgery. Furthermore, studies indicate that higher microbial concentrations often occur on the outer surface of the clothing system when the surgical staff visits uncontrolled environments outside the surgical departments.

Measurements of the cleanliness level have been performed in operating rooms classified as tissue and cells establishments for bone tissue to compare the results with the requirements given in the Tissue and Cells Directives of the European Union (EUTCD). The results show that the requirements are not always fulfilled. Common deficiencies in maintenance of e.g., HEPA filters are reported.

A theoretical study describes the influence of door-openings to the microbial air cleanliness of ultraclean air operating rooms for infection prone surgery. The results explain why door openings sometimes increase the level of airborne bacteria-carrying particles in the operating rooms. Temperature differences increase the air volume flows through the door openings and differences in concentration levels increase the contamination risks.

A comparison is presented between airborne cleanliness requirements for pharmaceutical manufacturing (EU GMP Annex 1) and recommendations for ultraclean air operating rooms and differences are discussed.

Keywords: Airborne contamination risks, Autoclaves, Contamination control, Microbial cleanliness, Tissue and cells establishments, Ultraclean air operating rooms, Source strength, Door openings

PREFACE

For over twenty years I have worked within in the field of contamination control and safety ventilation. The challenge of finding the optimal solution for contamination control to avoid contaminants from harming a person, a product or a process have been a driven force to learn more and deepen my knowledge in this area.

I have worked several years within the pharmaceutical industry (Pharmacia and AstraZeneca). Working in aseptic production raised my interest in designing high-efficiency particulate air filter units in order to protect openings of autoclaves and freeze dryers when doors are open. Appropriate design of these filter units is an important part to avoid airborne contamination of this process step in pharmaceutical manufacturing.

During my time working as a consultant, I had the opportunity to support tissue and cell establishments with cleanroom knowledge during their implementation of the new requirements (the Tissue and Cells Directives) for handling human tissue and cells within the European Union. Some of the tissue and cells establishments were handling bone tissue and their facilities consisted of operating departments for orthopedic surgery. The contact with tissue and cell establishments increased my interest of contamination control within operating rooms, especially operating rooms used for orthopedic surgery. I had the possibility to perform several studies in tissue and cell establishments and operating rooms used for orthopedic surgery with focus on environmental cleanliness and surgical clothing systems.

The research presented in this thesis is performed in the field of Safety Ventilation at Chalmers University of Technology, Department of Architecture and Civil Engineering, Division of Building Services Engineering.

Several persons have been significant for the progress and completion of this thesis:

My sincere thanks to my supervisors Professor Bengt Ljungqvist and Assoc. Professor Berit Reinmüller for their very important scientific guidance for over twenty years - from my time as a master student at KTH (The Royal Institute of Technology) until today in my daily work, and particular for this thesis. Their experience and knowledge in combination with their support, have been the key to the completion of this work.

My warmest gratitude to my examiner Professor Jan Gustén for accepting me at Chalmers University of Technology. I appreciate all supporting guidance thorough the process of this work.

I am so grateful to Ms. Maria Eklund and Ms. Tina Pettersson, registered nurses, who made several studies possible, and for all valuable discussions. Furthermore, a special thank to Ms. Jenny Sahlén, MSc. for assistance with the computational fluid dynamics study.

Special thanks to Mr. Mats Ogenborg, MSc, Mr. Håkan Sandholm, MSc, and Mr. Sture Sandholm, CEO of Energivärden Holding, for given me the opportunity to start and fulfill this project.

Furthermore, special thanks to Mr. Russell E. Madsen, MSc, President of the Williamsburg Group, Gaithersburg, Maryland, for his linguistic support.

Finally, I would like to express my sincere thanks to my family – Roger, Samuel and Sofie - for all support and encouragement. You are the best!

Stockholm, August 2019

Catinka Ullmann

CONTENTS

APPENDIX

A1 – Ullmann, C., Ljungqvist B., Reinmüller B., (2010), Design of HEPA-filter units in order to prevent airborne contamination of autoclaves and freeze dryers when doors are open, European Journal of Parenteral & Pharmaceutical Sciences, Vol. 15, No 2, pp. 53-59.

A2 – Ullmann, C., Ljungqvist B., Reinmüller B., Sahlén, J., (2012) Study of proper placements of HEPA-filter units in order to prevent airborne contamination of autoclaves in aseptic production by using computational fluid dynamics, European Journal of Parenteral & Pharmaceutical Sciences, Vol. 17, No 4, pp. 148-156.

A3 – Ullmann, C., Ljungqvist B., Reinmüller B., (2015), Requirements and environmental monitoring in pharmaceutical production versus operating rooms in hospitals with focus on airborne particles and microorganisms, European Journal of Parenteral & Pharmaceutical Sciences, Vol. 20, No 3, pp. 100-103.

A4 – Ullmann, C., Ljungqvist B., Reinmüller B., (2017), Microbial contamination risks of the surface of surgical clothing systems – an observational study, European Journal of Parenteral & Pharmaceutical Sciences, Vol. 22, No 1, pp. 6-12.

A5 – Ullmann, C., Ljungqvist B., Reinmüller B., (2017), Some aspects of protective efficacy of surgical clothing systems concerning airborne microorganisms based on results from measurements in a dispersal chamber and during surgical procedures, European Journal of Parenteral & Pharmaceutical Sciences, Vol. 22, No 2, pp. 51-58.

ABBREVIATIONS AND ACRONYMS

BC	Boundary Condition
CFD	Computational Fluid Dynamics
CFU	Colony Forming Unit
EU	European Union
EN	European Norm
EUTCD	European Union Tissue and Cells Directives
GAP	Gap Analysis Program
GMP	Good Manufacturing Practice
HEPA	High Efficiency Particulate Air
ISO	International Organization for Standardization
LR	Limitation of Risks
LVFS	Läkemedelsverkets föreskrifter
SAR	Surface Air Ratio
SIS	Swedish Institute for Standards
SOSFS	Socialstyrelsens författningssamling
SS	Swedish Standard
TSA	Tryptic Soy Agar

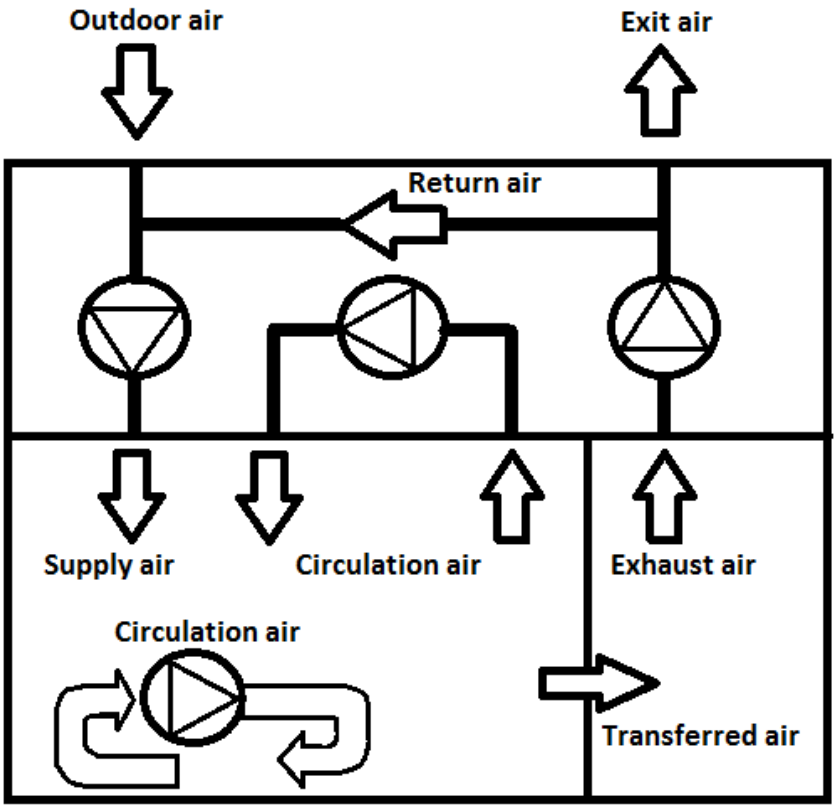
UDF	Unidirectional Flow
3D	Three Dimensional

TERMS AND DEFINITIONS

Active air sampling
Collection of bacteria-carrying particles from a specified volume of air, through collection on a filter or impaction on an agar surface.

Air change rate
The ratio between the air volume flow into or out of a room and the volume of the room. Normally expressed as the number of air changes per hour (ach).

Airflow nomenclature



Air volume flow
Volume of air transported per unit of time, specified in the unit m^3/s, l/s or m^3/h, also called airflow rate or shortened airflow.

Air velocity
The velocity of the air expressed in meters per second (m/s).

Autoclave
Process equipment used to sterilize instruments and packages by steam.

Cell and Tissue Establishment
An establishment handling tissue and cells (for example stem cells, bone tissue, heart valves and germ cells) for human application.

CFU (Colony Forming Unit)
Bacteria-carrying particle, which gives rise to a colony on a culture plate.

Clean air suit
Suit shown to minimize contamination of the operating room air from skin scales originating on the skin of persons.

Note: Clean air suits are medical technical products that meet the requirements set out in SS-EN 13795 and are designed to reduce the risk of airborne contamination.

Computational Fluid Dynamics (CFD)
The use of applied mathematics, physics and computational software to visualize how a gas or liquid flows based on the Navier-Stokes equations.

Critical zone
Dedicated space in the operating room, which covers the critical areas, including operating table and tables with the sterile instruments, in which the concentration of contamination (microbiological, gaseous and particulate) is controlled.

Differential pressure
Difference in air pressure between rooms.

Note: Specified in SI unit Pascal, Pa.

Dispersal chamber (”Body box”)
HEPA-filtered supply air test chamber with exhaust air in which the concentration of the total number of particles and bacteria-carrying particles from test subjects is measured in order to calculate the source strength.

HEPA filter
High Efficiency Particulate Air filter in accordance with SS-ISO29463.

Method of limitation of risks (LR-method)
Visualization of air movements, challenge tests and calculation of risk factors.

Microbial surface sampling
Collection of bacteria-carrying particles from a specified surface by contact plates or swabs.

Mixing airflow
Principle based on dilution of the contaminants by mixing the contaminated air with clean air, also called dilution mixing air or mixing air.

Non-unidirectional airflow
Air distribution where the supply air entering the cleanroom or clean zone mixes with the internal air by means of induction.

Operating room
Room, which is primarily intended for surgical operations.

Particle counter
An equipment used for count and size particles in the air.

Recovery time (Clean up time)
The time it takes to reduce the concentration of airborne particles to one hundredth of the original concentration (100:1).

Safety ventilation
Safety ventilation is the interaction between air movements and the dispersion of contaminants in environments and the control of these environments, both regarding human safety and the product or process safety/cleanliness.

Source strength
The average number of CFU or total number of particles released per second from one person wearing a specified clothing system.

Supply/Exhaust air devices
A device located in an opening provided at the boundaries of the treated space to ensure a predetermined motion of air in this space. Also, air terminal device.

Sterile supply center
Center within hospitals for cleaning and sterilization of reusable instruments and equipment.

Sterilization
A process that eliminates, kills or deactivates all forms of life.

Surgical clothing system
Dedicated gowning used by the staff within operating rooms.

Sweeping action of air
Transport of airborne contaminants by convective transport.

UDF system
Unidirectional airflow system is a distribution system for a room or a zone, aiming to displace contaminants by the sweeping action of the air.

Unidirectional airflow
Controlled airflow through the entire cross-section of a cleanroom or a clean zone with a steady velocity and air streams that are considered to be parallel.

Note: Principle based on transport of contaminants out of the critical zone by the sweeping action of the air.

Ultraclean air
Operating room air cleanliness during ongoing surgery of less than 10 CFU/m^3 of air.

Visualization
Characterization of air movement by visualization, e.g. using smoke tests.

SYMBOLS

A	Area, m^2
A_e	Area of exposed surface, m^2
c	Concentration; bacteria-carrying particles, CFU/m^3; total number of particles, number/m^3
c_0	Initial concentration; bacteria-carrying particles, CFU/m^3; total number of particles, number/m^3
c_b	Concentration of bacteria-carrying particles (CFU) uniformly distributed and constant, number/m^3
c_c	Constant concentration of bacteria-carrying particles in the corridor (ambient area), CFU/m^3
c_i	Constant concentration in the supply air; bacteria-carrying particles, CFU/m^3; total number of particles, number/m^3
c_{max}	Maximum steady-state concentration of bacteria-carrying particles, CFU/m^3
c_R	Constant concentration in the room (ambient area); bacteria-carrying particles, CFU/m^3; total number of particles, number/m^3
C_d	Discharge coefficient, non-dimensional
D	Diffusion coefficient, m^2/s
g	Gravitational acceleration, m/s^2

H	Opening height, m
n	Number of persons present, number
N_d	Number of bacteria-carrying particles deposited on a surface, number
N	Air change rate, 1/s also 1/h
q	Outward particle flow from point source; number/s
q_l	Outward particle flow per unit length from the line source, number/(s,m)
q_s	Source strength; mean value of the number of bacteria-carrying particles per second emitted from one person, CFU/s; mean value of the total number of particles emitted from one person, number/s
Q	Total air volume flow, m^3/s
Q_d	Flow rate through door opening in each direction, m^3/s
S	Total source strength; bacteria-carrying particles, CFU/s; total number of particles, number/s
t	Time, s
t_c	Closing time, s
t_e	Equivalent time, s
t_{exp}	Exposure time, s
t_h	Open hold time, s
t_0	Opening time, s
T	Time constant, s also min

T_0	Reference temperature, K
T_1	Temperature, K
ΔT	Temperature difference, K
v_0	Constant velocity in the x-direction, m/s
v_m	Mean air velocity, m/s
v_s	Constant settling velocity, m/s
V	Room volume, m^3
V_c	Chamber volume, m^3
V_d	Air volume pumped by moving door (50% of the swept volume of the door), m^3
W	Opening width, m
x, y, z	Positional coordinates
$\Delta\rho_0$	Density difference, kg/m^3
ρ_{om}	Mean density, kg/m^3
Θ_0	Maximal opening angle, rad

1 INTRODUCTION

Several industries have high demands of cleanliness requirements during their manufacturing processes in order to produce a product or process that fulfill the customers and the markets demands and expectations. Depending on type of product or process, the cleanliness requirement and what type of contaminants that are harmful may differ.

Within the hospital area the main source of contamination is microorganisms and some of them are antibiotic resistant. The number of airborne bacteria-carrying particles in operating rooms, and especially in operating room used for orthopedic prosthetic surgery, is considered as an indicator of the risk of infections to the patient undergoing surgery susceptible to infections. Premises used for tissue and cell establishments also have, in addition to requirements for airborne bacteria-carrying particles, requirements for total number of airborne particles and microorganisms on surfaces.

Contamination control requires design and development of the complete process in order to meet established cleanliness requirements. A successful fulfillment of the cleanliness requirements for a certain process are based on risk assessments and correct performances of several significant parameters.

Examples of such parameters are:

- The layout of the premises
- The HVAC principle within the premises and the amount of supply air
- Sterilization of material and equipment
- Clothing system for the personnel

- Working and cleaning procedures
- Logistics (Personnel-, material- and product flow)
- Periodical environmental and maintenance controls.

Even if just one of above specified parameters is failing, it may have a considerable negatively impact on fulfillment of the cleanliness requirements and thus on patient safety.

A sterile supply center is responsible to supply operating departments and other sections within the hospital area with sterilized materials and equipment. The sterile supply center uses autoclaves for sterilization of materials and equipment. Generally, there is a temperature difference when the door to the autoclave is opened after a process run. This can cause a flow of room air through the opening, creating a contamination risk.

A variety of clothing systems made of different fabrics are used within the hospital area, especially in operating room. Depending on type of fabrics, the clothing system may have different protective efficacy, i.e. source strength. The source strength is described as the number of airborne bacteria-carrying particles per second emitted from one person.

In order to create a unified framework for the procedure of handling human tissue and cells within the European Union, the Tissue and Cells Directives (EUTCD) were implemented 2007.The directives cover cleanliness requirements for the premises used for handling tissue and cells.

Purpose

The purpose of this work is to increase the awareness of contamination control and contamination risks within hospitals by:

- increasing the understanding of air movements and the dispersion of contaminants in autoclaves when doors to such equipment are open and establish a basis for dimensioning a HEPA-filter unit required for protection of the opening.
- investigation of the risk of contamination of the outside (surface) of surgical clothing system during a day of use and after visit to areas outside the operating room.
- evaluation of the source strength of different surgical clothing system during ongoing surgery and to investigate if the activity level of the personnel affects the result.
- performing measurement studies in premises used for tissue and cells establishments in order to investigate if the premises fulfill the European union requirements from 2007 regarding airborne particles, airborne bacteria-carrying particles and microorganisms in surfaces. The focus is on tissue and cells establishments used for bone tissues.
- explaining the influence of door-openings to the microbial air cleanliness of ultraclean air operating rooms for infection prone surgery.
- comparing premises for pharmaceutical aseptic manufacturing and ultraclean air operating rooms with regards to requirements and recommendations.

Delimitation

The measurements in this work is limited to autoclaves used for sterilization of material and equipment, clothing systems used in operating rooms and environmental cleanliness requirements in tissue and cells establishments.

Structure

This work begins with definitions and description of premises within Swedish hospitals and clothing systems for operating rooms. These are followed by a literature survey and a mathematical description of dispersion of airborne contaminants and contaminations risks. Thereafter materials and methods for all performed studies are described. The results of performed measurement studies and observations in hospitals are presented in separate chapters. The work also includes a chapter with theoretical aspects of door openings between operating rooms and adjacent rooms. The work ends with discussion and conclusion.

2 SHORT DESCRIPTION OF PREMISES

2.1 Sterile Supply Center

Instruments and equipment used by medical personnel within hospitals need to be clean and sterile. The cleaning and sterilization processes are performed in the sterile supply center, which is generally divided into four areas:

- Decontamination
- Assembly and sterile processing
- Sterile storage
- Distribution

A schematic process flow of reusable instruments and equipment between and within the sterile supply center and the surgical department is shown in Figure 2.1.

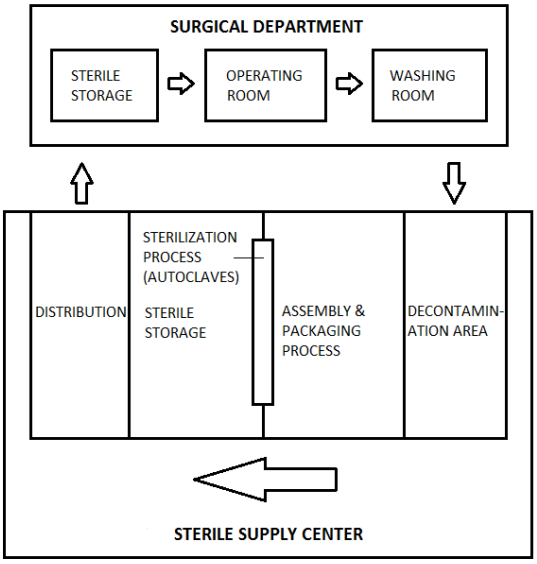


Figure 2.1 Schematic picture showing the process flow of the reusable instruments and equipment.

Decontamination area

In the decontamination area, reusable instruments and equipment, are cleaned and decontaminated.

The instruments and the equipment may have been cleaned once before at the operating department directly after use at an operation. The reason for the cleaning process at the operating department is to remove the contamination (blood, pieces of bone and other body secretions) as fast as possible from the instruments to prevent contamination to drain on/into the instruments and equipment. The purpose of the cleaning and decontamination process is to prepare the reusable instrument and equipment for the sterilization process but also protect the packing personnel from contact with disease-causing agents, see Figure 2.2.

Figure 2.2 Cleaning of used instruments and equipment in the surgical department (left) and the decontamination area within the sterile supply center (right).

Assembly and sterile processing

Before the sterilization of the instruments and equipment, some may need to be assembled into sets or trays according to recipe cards which give detail instructions for the assembling, see Figure 2.3 for example of a recipe card. Correct materials and packing techniques are important prerequisites for maintaining the sterility of the instruments and equipment from the sterilization process to the point of use.

Figure 2.3 Example recipe card for packing instruction.

Autoclaves are used to sterilize the instruments and equipment by heating them with steam to a very high temperature. The first step in an autoclave process is to remove the air from both the load and the chamber. The most effective way of air removal is to use a vacuum system. Once the air has been totally removed, the sterilization process can start by exposing the load and the chamber to steam. The wet heat kills bacteria, virus and other organisms. Depending on type of load the sterilization cycle and temperature vary but a typical cycle runs from 3 to 20 minutes and the temperature range can be about 120-135˚C.

Figure 2.4 shows personnel packing instruments and equipment and loading them into the autoclave for the sterilization process.

Figure 2.4 Packing of instruments and equipment (left) and loading of equipment and instruments into the autoclave (right).

Sterile storage

The instruments and the equipment may be used directly after the sterilization, but they may need to be stored for a longer period. The sterile supply center therefore needs a room for storage of sterilized instruments and equipment, see example of a storage room in Figure 2.5. The storage room is normally located is adjacent to the unloading area of the autoclaves. Example of an unloading area see Figure 2.5.

Figure 2.5 Sterile storage (left). Unloading area of autoclaves (right).

Distribution

Sterilized instruments and equipment are on a regular basis transported to the surgical department and other departments within the hospital. An airlock adjacent to the sterile storage area may be used as a distribution point for instruments and equipment for further transportation within the hospital.

Room air distribution systems

The room air distribution system for sterile supply center is normally dilution mixing air. Some working places in the packing room may be provided with unidirectional airflow but the most common solution is dilution mixing air for the entire room.

The air distribution system provides the sterile supply center with a positive pressure difference to adjacent rooms or departments. Within the sterile supply center, the room used for sterile storage has a positive pressure difference to the packing room and the distribution area.

2.2 Operating Room

An operating room used for orthopedic surgery is also described as an ultraclean air operating room due to infection-prone surgery and the importance of maintaining high cleanliness during the surgery.

An ultraclean air operating room can either have HEPA-filtered dilution mixing air as the room air distribution system, or it may be equipped with unidirectional airflow (UDF) unit, see Figure 2.6.

Figure 2.6 Operating room with dilution mixing air (left). Operating room with vertical unidirectional airflow (right).

The layout for the surgical department varies between different hospitals. The entry and exit to the operating room are normally from an adjacent corridor used for all the personnel working within the surgical department. In some cases, the operating room is provided with an airlock for entry and exit. The operating room is often located against an outer wall and is adjacent to a preparation room(for patient) or an instrument lay-up room. The room air distribution system in the operating room provides the room with a positive pressure difference to adjacent rooms. Examples of different layouts for surgical departments are shown in Figure 2.7.

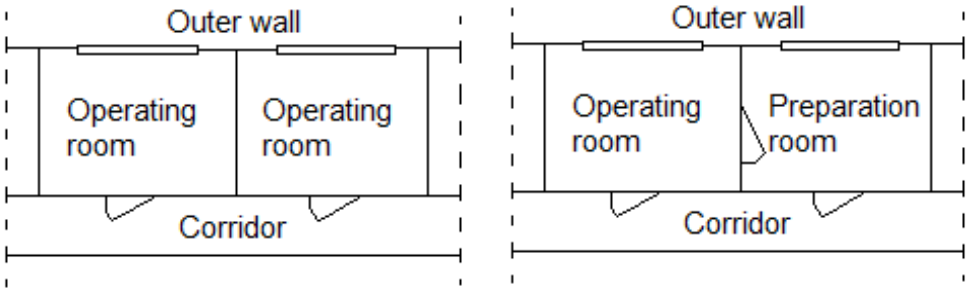


Figure 2.7 Examples of different layouts for surgical departments.

Before the start of surgery, sterile instruments and equipment are transported into the operating room through the door from the corridor/airlock. A pass-through cabinet is used for intake of additional material during surgery, see example of a pass-through cabinet in Figure 2.8.

Figure 2.8 Example of a pass-through cabinet between an operating room and outside corridor.

2.3 Instrument Lay-up Room

Preparation and laying-up of sterile instruments before a surgical operation may be performed within the operating room or in a separate and dedicated room. The room can either be adjacent to the operating room or located centrally within the operating department.

A lay-up room serve 2-3 operating rooms, and the use of a lay-up room may increase the number of surgeries in the operating room due to faster changing time between patients.

The room air distribution system for lay-up rooms can either be HEPA-filtered dilution mixing air or a unidirectional airflow (UDF) unit. The lay-up room has a positive pressure difference to adjacent operating rooms.

Some surgical departments use also mobile lay-up tables in the operating room.

The mobile lay-up table has an integrated horizontal airflow system, see Figure 2.9, with the purpose of protecting the sterile instruments from microbial contamination from the surrounding environment in the operating room.

Figure 2.9 Example of mobile lay-up tables for sterile instruments in operating rooms.

2.4 Tissue and Cells Establishment

Tissue and cells establishment is handling tissues and cells for human application, i.e., patient treatment. Examples of human tissue and cells used for patient treatment are stem cells, bone tissue, corneas, derma, heart valves, cellular therapies and germ cells.

Depending on type of human tissue and cells the establishment is handling, the layout and the installation of premises may vary. Some tissue and cells establishments are built as laboratories with UDF benches, for example, establishments for germ cells, while establishments for bone tissue are accomplished in operating rooms for orthopedic surgery. Figure 2.10 shows pictures from a germ cells establishment and an operating room used for bone tissue procedures, respectively. The operating room in this case is equipped with horizontal unidirectional airflow, which is not common in operating rooms used as a tissue and cells establishment. Many operating rooms for bone tissue procedures have dilution mixing air as room air distribution system, while others have unidirectional airflow in the operating room.

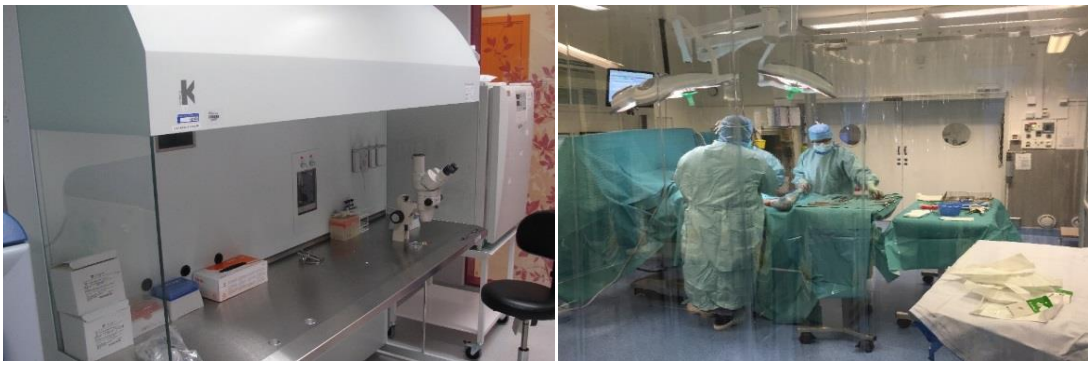


Figure 2.10 A tissue and cells establishment for germ cells (left). Operating room used for bone tissue procedure (right).

2.5 Room Air Distribution Systems

Main air distribution systems

The objectives for the ventilation system for operating rooms are to create a satisfying environmental for the personnel and patient by supplying the room with correct temperature and fresh air but also for contamination control within the room.

There are two main room air distribution systems for operating rooms:

- Mixing airflow distribution system
- Unidirectional airflow distribution system

Mixing airflow distribution system

Mixing airflow distribution system is based on a concept of mixing incoming air with air present in the room, see Figure 2.11. The supply airflow dilutes the contaminated air with cleaner before the mixed air is exhausted from the room through exhaust air devices.

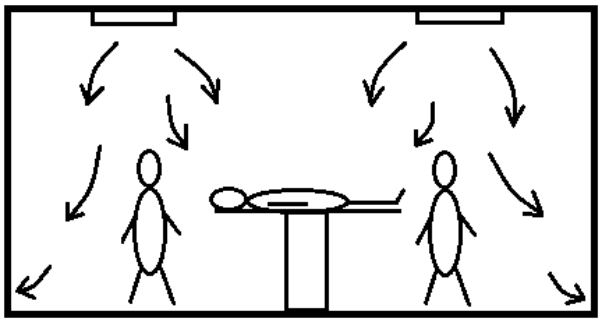


Figure 2.11 Operating room with mixing airflow distribution system.

Unidirectional airflow distribution system

A unidirectional airflow distribution system can either be designed as a vertical or horizontal unidirectional airflow, see Figure 2.12.

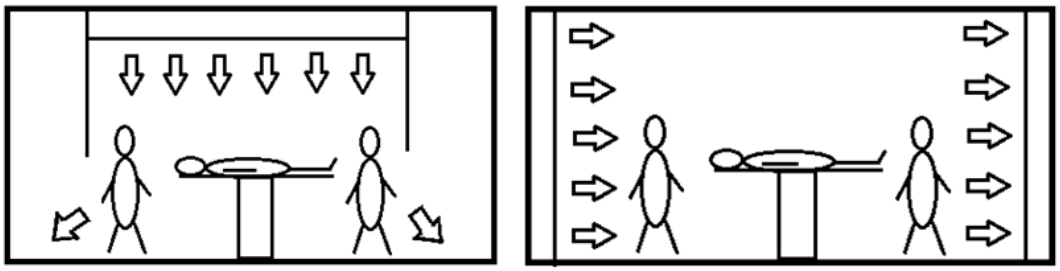


Figure 2.12 Operating rooms with unidirectional airflow systems. Vertical unidirectional airflow (left) and horizontal airflow (right).

The system is based on a sweeping action concept; airborne contaminants within the critical area is swept away by the unidirectional airflow due to a convective transport. Figure 2.13 is showing the sweeping action of a unidirectional airflow distribution system in an operating room.

Equipment and installations in the operating room may generate disturbances within the unidirectional airflow and create areas of non-unidirectional airflow.

Figure 2.13 Sweeping action of a unidirectional airflow system in an operating room.

Combination of the main air distribution systems

There are systems based on a combination of mixing airflow system and unidirectional airflow system, see Figure 2.14.

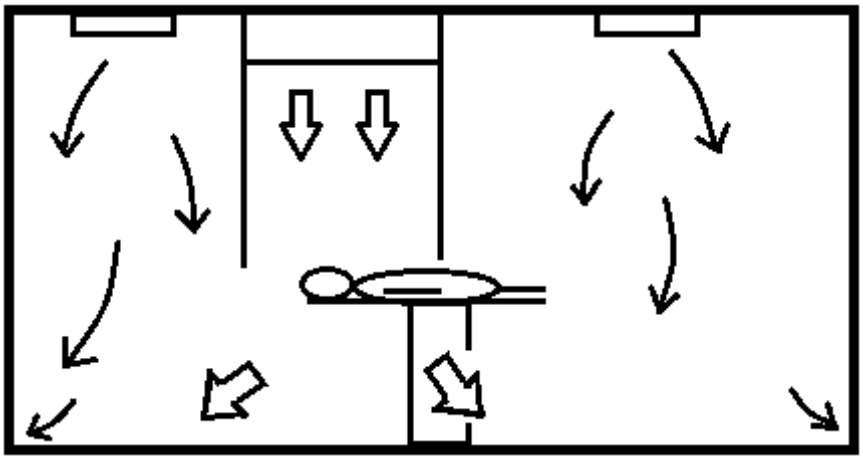


Figure 2.14 Operating rooms with a combination of mixing airflow system and unidirectional airflow system.

Parameters for air distribution systems

Important parameters for air distribution systems in operating rooms are:

- Air volume flow
- Air changes per hour
- Recovery time (clean-up time)
- Air velocity
- Filtration of the air
- Air movements

2.6 Requirements

Cleanliness requirements and recommendations - airborne particles and microorganisms – for sterile supply center, surgical department and tissue and cells establishment, are specified in the following documents:

- *SS 8760015:2017*
  Basic requirements for transportation, storage and handling of sterile medical devices intended to be used within health care
- *SIS TS 39:2015*
  Microbiological Cleanliness in the Operating Room – Preventing Airborne Contamination – Guidance and Fundamental Requirements
- *The European Union Tissue and Cells Directives, EUTCD*

SS 8760015:2017

This is a new Swedish standard with focus on requirements for transportation, storage and handling of sterile medical devices intended to be used within the hospital area. The standard includes airborne particulate and microbial cleanliness requirements for storage areas, see Table 2.1. The standard also includes requirements for ventilation, cleaning, etc.

The supply air for the storage areas should be terminally filtrated with high efficiency particulate air filters, i.e., HEPA.

Table 2.1 Airborne particulate and microbial requirements for storage areas according to SS 8760015:2017.

Airborne contaminants In operation	Limits according to SS 8760015:2017
Maximum permitted particles/m^3	
≥0.5µm	Not defined
≥5µm	Not defined
CFU/m^3 active sampling	≤ 100
CFU/m^3 passive sampling	≤ 50
Microbial cleanliness on surface CFU/5.5 cm^2	≤ 25

SIS TS 39:2015

Cleanliness requirements (airborne particles and microorganism) for ultraclean air operating rooms and the procedure for environmental monitoring differ between countries in Europe. In Sweden the levels of airborne particles and colony forming units (CFUs) are monitored during ongoing surgery in the operating room while other countries monitor the operating rooms at rest.

In addition to the recommendation of airborne microbial cleanliness, the technical specification also provides guidance for design of operating rooms (layout and heating, ventilation and air conditioning), environmental monitoring, surgical clothing systems, cleaning, etc.

The recommendation of airborne microbial cleanliness in ultraclean air operating rooms according to SIS-TS 39:2015 (2015), is specified in Table 2.2.

Table 2.2 *Summary of limits for ultraclean air operating rooms according to SIS-TS 39:2015, regarding airborne particles and microbial contamination.*

Airborne contaminant	Limits according to SIS-TS 39:2015
At rest:	
Maximum permitted particles/m^3	
≥0.5µm	3520
≥5µm	29
During surgery:	
Maximum permitted particles/m^3	
≥0.5µm	Not defined
≥5µm	Not defined
CFU/m^3	10

The European Union Tissue and Cells Directives, EUTCD

The European Union implemented in 2007 the Tissue and Cells Directives, EUTCD, to create a unified framework for the procedure of handling human tissue and cells within the European Union to secure the human health related to the application of cells and tissues to the human body. The directives cover safety and quality for donation, procurement, testing, processing, preservation, storage and distribution.

The EUTCD consists of three directives:

- European directive 2004/23/EC (Parent directive)
- European directive 2006/17/EC (First technical directive)
- European directive 2006/86/EC (Second technical directive)

A third technical directive was implemented 2012; European directive 2012/39/EU.

The 1st of July 2008, Sweden adopted the new law based on the Tissue and Cells Directives, and the valid Swedish law and directives are:

- Lag 2008:286 om kvalitets- och säkerhetsnormer vid hantering av mänskliga vävnader och celler*(quality and safety procedures during handling of human tissue and cells)*
- SOSFS 2008:30 Socialstyrelsens föreskrifter om donation och tillvaratagande av vävnader och celler *(donation and procurement of tissue and cells)*
- SOSFS 2009:31 Socialstyrelsens föreskrifter om vävnadsinrättningar i hälso- och sjukvården m.m. *(tissue and cells establishments within healthcare)*
- SOSFS 2009:32 Socialstyrelsens föreskrifter och allmänna råd om användning av vävnader och celler i hälso- och sjukvården och vid klinisk forskning *(use of tissue and cells within healthcare and in clinical research)*

If tissue and cells are used as raw material for pharmaceutical manufacturing or used for pharmaceutical products for advanced therapy, the following regulations are valid:

- LVFS 2008:12 Läkemedelsverkets föreskrifter om hantering av mänskliga vävnader och celler avsedda för läkemedels-tillverkning
- LVFS 2011:3 Läkemedelsverkets föreskrifter om läkemedel som omfattas av sjukhusundantaget

Appendix 2 to SOSFS 2009:31 specifies the air quality and cleanliness requirements for the premises used for processing of tissue and cells. The directive refers to the European Guide to Good Manufacturing Practice (EU GMP) and state that premises used for processing of tissue and cells shall fulfill grade A at the area for the processing and the background environment shall at least fulfill grade D. The requirements for airborne particles, airborne bacteria-carrying particles and microorganisms on surfaces according to EU GMP Annex 1 (2008) are summarized in Tables 2.3 and 2.4.

Table 2.3 Maximum permitted number of airborne particles according to EU GMP Annex 1 (2008).

Grade	Maximum permitted number of particles per m^3 ≥ the tabulated size			
	At rest		In operation	
	0.5µm	5.0µm	0.5µm	5.0µm
A	3520	20	3520	20
B	3520	29	352 000	2900
C	352 000	2900	3 520 000	29 000
D	3 520 000	29 000	*Not defined*	*Not defined*

Table 2.4 Recommended limits for microbial contamination according to EU GMP Annex 1 (2008).

Grade	Recommended limits for microbial contamination			
	Air sample CFU/m^3	Settle plates (diameter 90 mm) CFU/4 hours	Contact plates (diameter 55mm) CFU/plate	Glove print 5 fingers CFU/glove
A	< 1	< 1	< 1	< 1
B	10	5	5	5
C	100	50	25	-
D	200	100	50	-

Appendix 2 to SOSFS 2009:31 also specifies the following criteria when it is acceptable to lower the air quality and cleanliness requirements:

a) Reliable methods for inactivation of microorganisms or final sterilization are used.

b) If exposure in a grade A environment may harm the quality of the tissue and cells.

c) If it can be demonstrated/proven that there is a decreased risk for bacterial and fungal infection for the receiver compared to transplant.

d) It is not possible in a technical aspect to perform the processing within a grade A environment.

3 CLOTHING SYSTEMS

3.1 Source Strength

The source strength is described as the average number of airborne bacteria-carrying particles per second or total number of particles emitted from one person dressed in a specified clothing system.

With the assumption of mixing airflow, no leakage into the operating room, and the HEPA filters having efficiency close to 100 percent, the simplest possible expression, which is applied on the dilution principle, describes the source strength, protective efficacy of surgical clothing system (outward particle flow). The expression of the source strength becomes:

$$q_s = c \cdot Q/n \qquad (3.1)$$

where q_s = mean value of source strength; bacteria-carrying particles (CFU/s) or particles (number of particles/s) emitted from one person dressed in a specified clothing system

c = concentration; bacteria-carrying particles (CFU/m^3) or particles (number of particles/m^3)

Q = total air volume flow (m^3/s)

n = number of persons present, (number)

The source strength value is influenced by the material properties, design of the clothing system, and the activity level of the person.

An example of calculation according to Equation (3.1)

An operating room has a cleanliness requirement (maximum level of bacteria-carrying particles) of ≤10 CFU/m^3, a total airflow of 0.6 m^3/s and 6 persons present during ongoing surgery, see Figure 3.1.

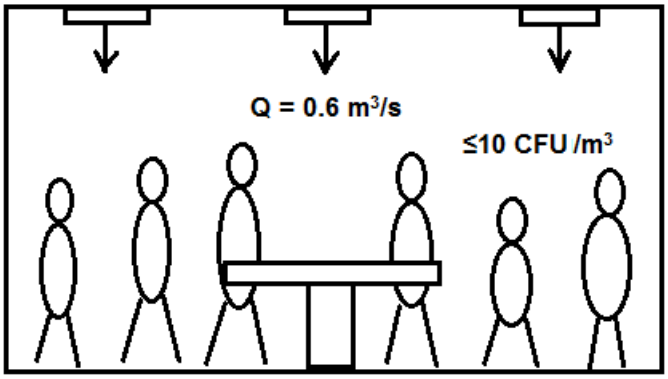


Figure 3.1 Example of an operating room with a total airflow of 0.6 m^3/s, 6 persons present and a cleanliness requirement of ≤10 CFU/m^3.

Which source strength value does the clothing system need to fulfill to maintain the cleanliness requirement of ≤10 CFU/m^3 within the operating room?

By using Equation (3.1), the value of the source strength in the example can be calculated by

$$q_s = 10 \cdot 0.6/6 = 1 \text{ CFU/s}$$

For the operating room in this example, the personnel need to wear clothing system with a source strength of equal or below 1 CFU/s to fulfill the cleanliness requirement of ≤10 CFU/m^3 based on a total airflow of 0.6 m^3/s and 6 persons present during ongoing surgery.

3.2 Functional Surgical Clothing Systems

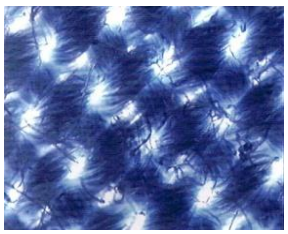
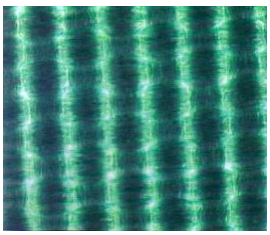
In operating rooms for surgery susceptible to infections, the selection of surgical clothing systems can be important. The personnel in an operating room is the main source of bacteria-carrying particles and the surgical clothing system works as a filter protecting the environment against airborne contamination.

The filter effectiveness of the surgical clothing system depends on several factors as:

- Type of fabric
- Design of the clothing system
- Aging
- Laundering

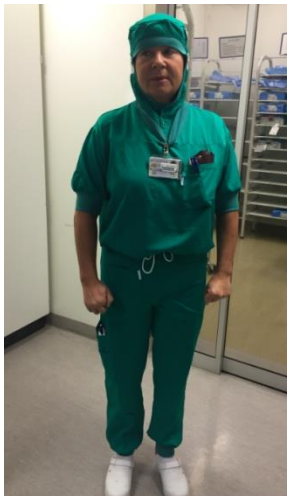
The air permeability, particle retention, and the pore size of a fabric are significant characteristics when evaluating the fabric suitability to be used in surgical clothing system. Some of the surgical clothing systems are made of fabrics based on a mix of organic material (cotton) and synthetic fibers while the fabric in other clothing systems is based on only synthetic fibers. Table 3.1 gives example of the composition of fabrics in different surgical clothing systems and shows pictures of the structure of the different fabrics (Ljungqvist and Reinmüller (2013)).

Table 3.1 Examples of composition of the fabrics in different surgical clothing system.

	Surgical clothing system	
	A	B
Type of fabric	Cotton (69%) Polyester (30%) Carbon fiber (1%)	Polyester (99%) Carbon fiber (1%)
		

Clothing systems have different designs depending on manufacturer, fabrics etc. Figure 3.2 shows surgical staff wearing three different clothing systems; of mixed material, of Olefin, and of disposable material. The clothing system made of Olefin has a textile surgical helmet made in the same fabric while the other two clothing system have surgical helmets of disposable material.

Clothing system of mixed material



Clothing system of Olefin

Clothing system of disposable material

Figure 3.2 Three common clothing systems.

Surgical clothing system used in Sweden give often the user option to choose shoes for the operating room. As an option to improve the clothing system, it can also include knee-length boots, see Figure 3.3.

Figure 3.3 Clothing system with knee-length boots.

The use and laundering of the clothing systems decrease the fabrics efficiency to protect the surrounding environment from the dispersion of bacteria-carrying particles from the personnel. The source strength of a clothing system may therefore increase with time. The age and the numbers of washings before the efficiency of the fabric is negatively affected, vary between different clothing systems and have been investigated and discussed by Reinmüller and Ljungqvist (2000, 2003)Ljungqvist and Reinmüller (2004, 2006, 2014) and Romano et al (2016). The efficiency of a clothing system can be evaluated in a dispersal chamber and give valuable information of a clothing system source strength, life-span etc., see Part 3.4 Evaluation of Clothing Systems.

3.3 Logistic and Storage

Clothing systems need to be transported to and from the hospital and within the hospital. During the transports, there may be an increased risk of contamination of the clothing system and therefore the transport procedures should be risk analyzed and potential contamination risks and/or situations identified.

The clothing systems should be washed in a validated process at correct temperature 72°C and be properly packed in a controlled environment to ensure the cleanliness. The transport from the laundry should prevent contamination of the clean clothing system.

The personnel changing room need to be designed with a suitable storage space for the clothing system as well for enough space for the personnel to change to the surgical clothing system without risk of contamination of the clothing during the changing procedure. The clothing system should preferable be stored within a cabinet with doors compared to on open shelves, see example in Figure 3.4, due to higher contamination risk of the clothing system.

Figure 3.4 Example of storage of clothing system in a changing room within a hospital.

It is of importance to identify the personnel flow and material transport within the hospital to avoid cross contamination. The handling of clean clothing system should be separated from handling of used clothing systems that should be either wasted or sent for washing.

3.4 Evaluation of Clothing Systems

The European Standard EN 13795-2 (2019) “Surgical clothing and drapes – Requirements and test methods – Part 2:Clean air suits” specifies test methods for evaluation of operating clothing systems. For example, to evaluate the design and material of a clothing system, tests in a dispersal chamber could be performed. The principal arrangement of a dispersal chamber is shown in Figure 3.5. The chamber consists of tightly sealed walls and a door. The inflow of air into the chamber is HEPA-filtered and the chamber has a positive pressure difference to the surroundings of approximately 10 Pa. In the test chamber the air is unidirectional and in the exhaust air duct turbulently mixed.

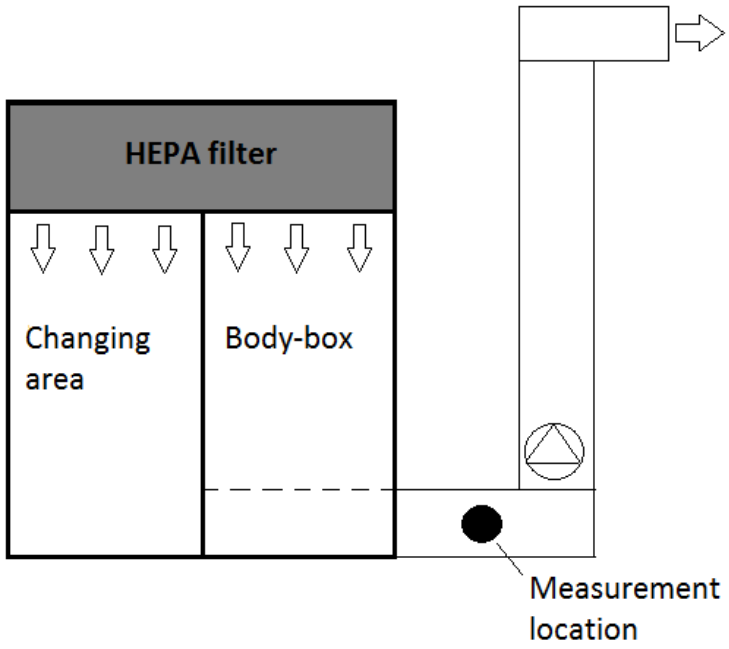


Figure 3.5 Principal arrangement of dispersal chamber (body-box).

During evaluation of a clothing system, male test persons dressed in the clothing system performs standardized cycles of movements in the body-box. By using the air volume flow in the dispersal chamber in combination with the measured concentrations, the source strength (the total number of particles or bacteria-carrying particles

per second emitted from one person) of a clothing system can be calculated.

During the measurements, the test subjects perform standardized cycles of movements that include arm movements, knee bends and walk in place at a set speed. These movements are, in principle, comparable with those described in IEST-RP-CC003.4 (2011). Prior to each cycle of movement, the test subject stands still to avoid the influence of particle generation from the previous test cycle. Each evaluation occasion has the same five test subjects performing the standardized cycles of movements four times, see Ljungqvist and Reinmüller (2004).

Source strength evaluated during orthopedic surgery is approximately half of the result achieved from dispersal chamber tests due to considerable higher activity level in the dispersal chamber, see Ljungqvist at al (2014) and Ullmann et al (2017b).

Examples of surgical clothing systems that have been tested and evaluated in a dispersal chamber by Ljungqvist and Reinmüller (2004, 2014) and described by Ullmann et al (2017b) are:

- Clothing system of mixed material (69% cotton, 30% polyester, 1% carbon fiber), see result in Table 3.2.
- Clothing system of fabric Olefin (98% olefin, 2% carbon fiber), without and with textile knee-length boots, see result in Table 3.3.

Table 3.2 Source strength mean values of aerobic CFU from dispersal chamber tests with five test subjects dressed in clothing system of mixed material (69% cotton, 30% polyester and 1% carbon fiber).

Test subject	Source strength (CFU/s)	
	Mean value *	Min – Max*
1	2.5	1.5 – 4
2	7.5	6 – 8.5
3	10.1	7 – 12.5
4	8.6	8 – 10.5
5	10.3	6.5 - 15
Grand mean value	7.8	N/A

* Numbers are given with one decimal

Table 3.3 Source strength mean values of aerobic CFU from dispersal chamber tests with five test subjects dressed in Olefin clothing systems with textile hood. Additionally, open plastic shoes (sandals) was worn without and with textile knee-length boots.

Test subject	Source strength mean values (CFU/s)*	
	Without boots	With boots
1	1.4	1.2
2	0.7	0.2
3	3.1	0.8
4	2.4	0.6
5	3.8	2.3
Grand mean value	2.3	1.0
Min – max	0.7 – 3.8	0.2 – 2.3

* Numbers are given with one decimal.

4 LITERATURE SURVEY

4.1 Introduction

Even if contamination control and cleanroom technology is a modern technology, the development of contamination control started about 100 years ago within the hospital area. At this time, some microbiologists and surgeons as Pasteur and Lister understood the importance of reducing the amounts of bacteria-carrying particles within the hospital area, and especially in the operating rooms, in order to prevent wound infections.

But even earlier there were pioneers, who understood the relatedness between cleanliness and increased opportunity to survive and recover from diseases or injuries, for example Ignaz Semmelweis and Florence Nightingale.

Ignaz Semmelweis was a physician and worked in the mid-1800s in Vienna General Hospitals First Obstetrical Clinic. He discovered that the risk for patient to become sick and die of childbed fever decreased if the personnel at the clinic used hand disinfection.

Florence Nightingale, see Figure 4.1, was a nurse in England who led a group of nurses during the Crimean War in the mid-1850s with the mission to nurse wounded soldiers. To increase the possibility for the soldiers to survive their wounds, Nightingale realized that the hospital needed to be properly managed. By improving the cleanliness and the ventilation in the hospital, the bacterial infections were reduced, and more soldiers survived.

Figure 4.1 A watercolor portrait of Florence Nightingale at the "Florence Nightingale Museum" in London (photo C. Ullmann).

Figure 4.2 shows a ventilation solution for a room in a hospital in the 1920s (Whyte 1999). The patient has the possibility to inhale fresh air from the funnel close to the bed and foul air from the floor in extracted from the funnel at the window.

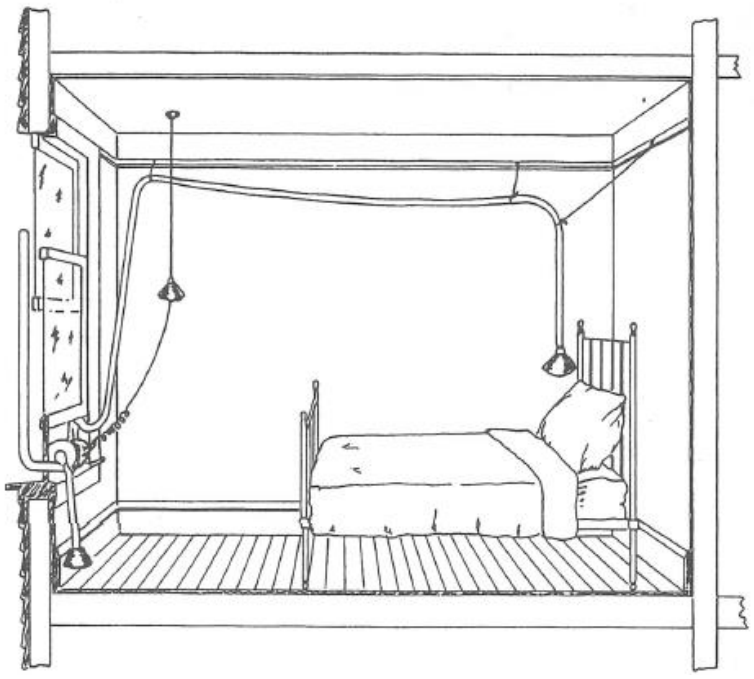


Figure 4.2 Ventilation solution in a room in a hospital in the 1920s (Whyte (1999)).

4.2 Room Air Distribution Systems

Development of airflows in operating rooms

Mechanical ventilation in hospitals was at the beginning used more for comfort than for reducing bacteria-carrying particles. During the 1940s Bourdillon et al (1948) performed studies in hygiene and after the end of the second world war mechanical ventilation started to be installed in hospitals for contamination control.

Blowers and Crew (1960) performed tests on different air distribution system and established that approximately 20-25 air changes per hour is adequate in rooms with dilution mixing air. The results improved more or less proportionately up to this level but a higher amount of air changes per hour only gave a smaller improvement.

The book *Hospital Infection* by Williams et al (1960) suggested an airflow of minimum 15 air changes per hour in rooms with dilution mixing air.

After performing tests in a room with unidirectional airflow, Whitfield (1967) presented 0.5m/s as a design value of the air velocity of the airflow. The design value was based on the compromise between needed clean-up time for the airborne bacteria-particle in the complete area and the personnel comfort working in the unidirectional airflow.

Tests performed in operating rooms with unidirectional airflow (both vertical and horizontal) by Whyte et al (1973), showed that air velocities in the range of 0.3-0.4m/s gave maximum returns of effort.

Development of ultra clean air distribution systems

Room air distribution system based on dilution mixing air was well known in the beginning of the 1960s. At this time it was also established that the people were the source of bacteria-carrying particles in an operating room.

A new solution for reducing bacteria-carrying particles within operating rooms was developed in the early 1960s by Professor Sir John Charnley (1964, 1972). He created a room, called a "greenhouse", within the operating room. The "greenhouse" had a filtered supply air with downward air movements, see Figure 4.3. To be able to counteract rising air movements caused by the surgical staff, Charnely stated that the airflow rate should be at least 100 air changes per hour. Charnley and Eftekhar (1969) later stated that if the air changes rate increased to 300 air changes per hour, further improvements were achieved.

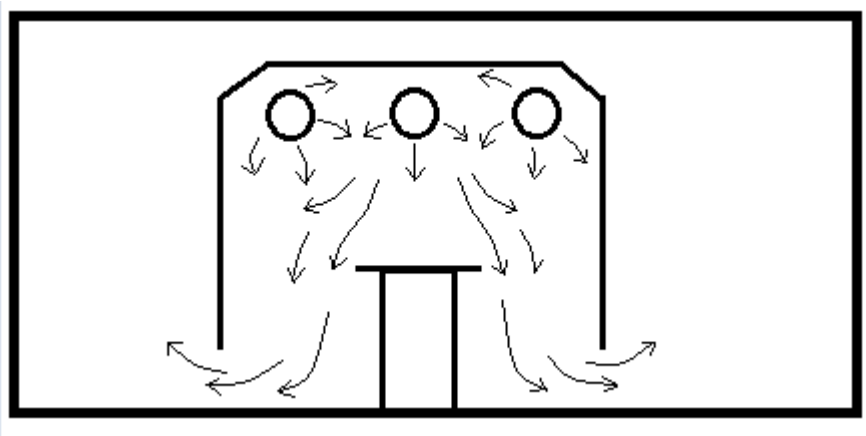


Figure 4.3 The "greenhouse" by Charnley.

Another concept was also developed during the 1960s, called the Allander air curtain system, see Figure 4.4. The inner material walls in vertical unidirectional unit were replaced by air curtains, see Allander (1965) and Abel and Allander (1966). Depending on the size of the inner zone, the air change rate is 100-140 air changes per hour (3200-5800 m^3/h).

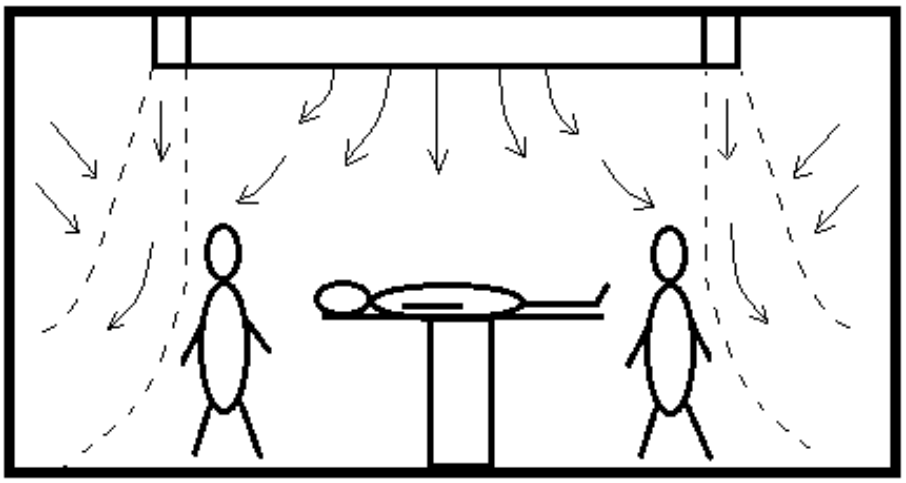


Figure 4.4 The Allander air curtain system.

In the 1970s unidirectional airflow units (UDF-units) with vertical or horizontal airflow started to be used (see Figure 2.12). Horizontal unidirectional airflow units are nowadays not commonly used in Sweden. Figure 4.5 is showing a vertical unidirectional airflow unit with barrier walls according to Charnley´s principle. The air velocity of the airflow was approximate 0.4-0.5m/s and the total airflow was 6-8 times higher compared to conventional operating rooms with dilution mixing air.

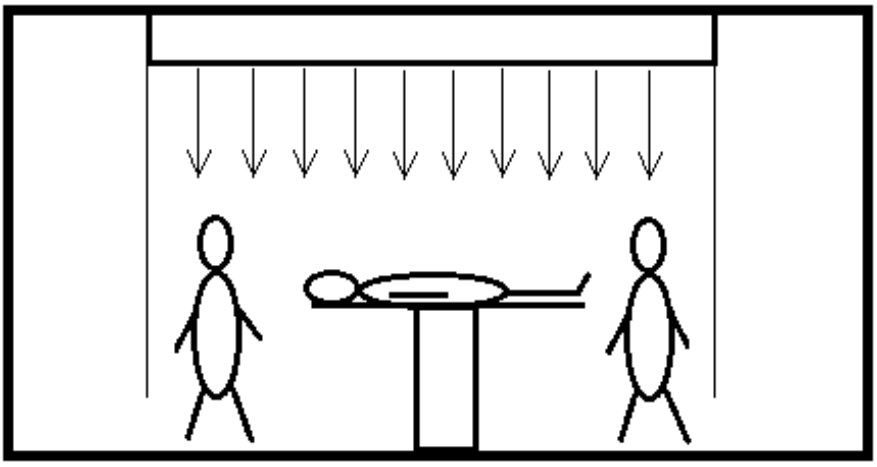


Figure 4.5 A vertical unidirectional airflow unit with barrier walls according to Charnley´s principle.

During the 1980s, Howorth (1980, 1984, 1985) presented a system called “Exflow”, see Figure 4.6. The “Exflow” is an air system without walls and where the airflow pattern is like the mouth of a trumpet facing downward. The idea with this design was that the downward and outward air movement are able to prevent entrainment of contaminants from the outer zone in the operating room and from the floor.

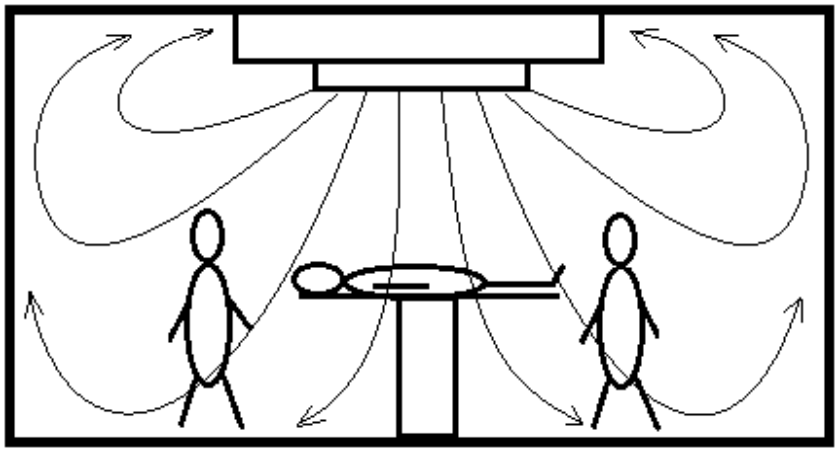


Figure 4.6 The “Exflow” system of Howorth.

The design of the barrier walls on unidirectional airflow units was changed to partial walls, see Figure 4.7, during the 1990s. The airflow velocity was reduced from 0.4-0.5m/s to ≤0.3m/s which gives a total airflow of 3-5 times higher compared to conventional operating rooms with dilution mixing air.

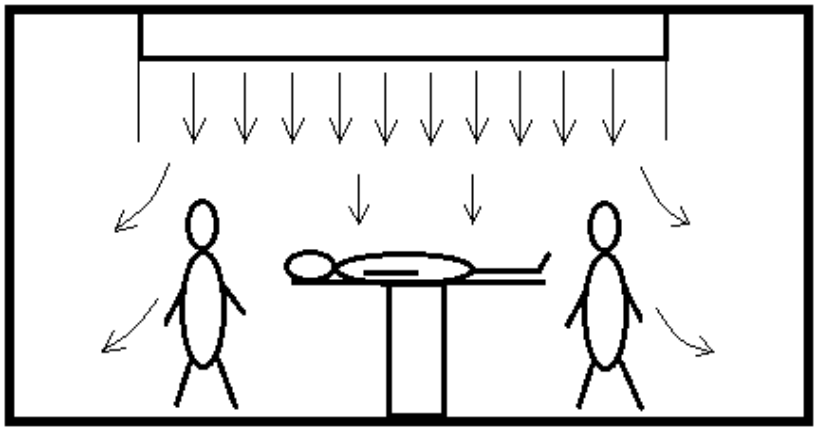


Figure 4.7 A unidirectional airflow unit with partial walls.

Nordenadler (2010) has performed measurement studies in operating rooms with unidirectional airflow units. The air velocity of the downflow was below 0.3m/s. The study showed that the unidirectional airflow was not maintained above the operating table. Instead an airflow pattern with disordered manner occurred which resembled mixing air, see Figure 4.8.

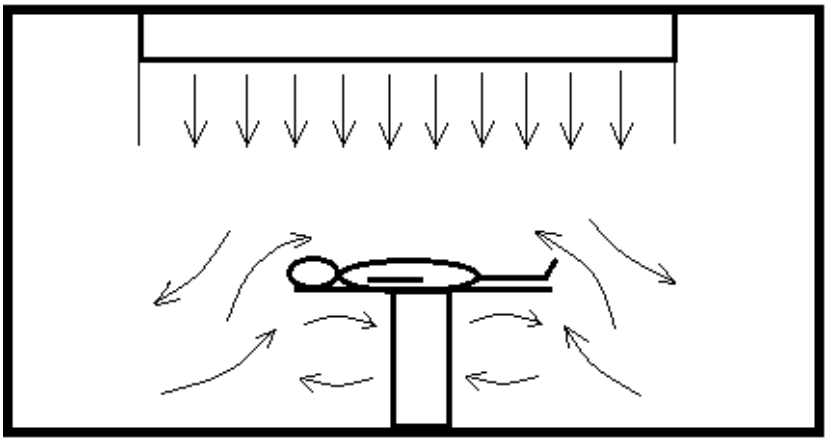


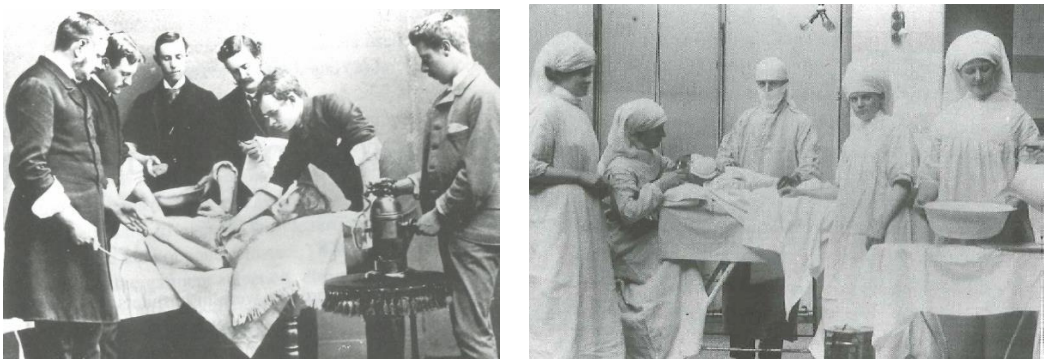
Figure 4.8 Airflow pattern with disordered manner above the operating table which resembles mixing air.

In Sweden today, an airflow of 2-3m^3/s is usually chosen for ultra clean air operating rooms, independently of type of room air distribution system.

4.3 Clothing Systems

Back in time surgeons did not wear specific clothing systems for surgical procedures. Their clothes were exposed to different environments and other patients.

Figure 4.9 shows pictures of surgical staff in Scotland in 1889 and in 1907 respectively. The pictures illustrate the progress of cleanliness and the understanding of the need to eliminate the level of airborne bacteria-carrying particles in the operating room to prevent infections. The picture from 1889 is showing surgeons in different suits while the picture from 18 years later is showing surgical staff with dedicated clothing system for the operating room, their head is covered, and the surgeon is wearing a protective mask for his mouth.



1889 1907

Figure 4.9 Surgical staff in Scotland in 1889 (to the left) and 1907 (to the right) (from Whyte (2001)).

The surgical clothing system importance for reducing the level of airborne bacteria-carrying particles in an operating room has been discussed and described by several, for example Charnely (1972). The developer of the "greenhouse" within the operating room, stated that it is possible with further reduction of the infection rate by using a special surgical clothing system (a body-exhaust suit).

The fabric of the clothing system has an impact of the bacterial dispersion rate from a person wearing a specified clothing system. According to Whyte et al (1990) clothing system of polyester was demonstrated to be much superior to conventional cotton clothing

system and at least as good as the total body exhaust gowns and disposable clothing. An evaluation of air quality in operating rooms with three different clothing systems performed by Friberg (1998), showed that disposable clothing system generated decreased level of airborne bacteria-carrying particles compared to clothing systems of cotton.

The source strength (the average number of airborne bacteria-carrying particles per second or number of particles per second emitted from one person dressed in a specified clothing system) varies with clothing systems and has been presented by Whyte (1999), Reinmüller (2001), Ljungqvist and Reinmüller (2004, 2006, 2014), Whyte and Hejab (2007), Ljungqvist et al (2012, 2014), and Tammelin et al (2012, 2013). A literature survey has also been performed by Ljungqvist and Reinmüller (2013). Following references will be discussed here:

- Reinmüller (2001)
  Evaluation of different cleanroom clothing systems by a case study. The study consisted of measurements performed in a dispersal chamber and calculation of source strength value for the different clothing systems.

- Ljungqvist and Reinmüller (2004)
  A surgical clothing system of mixed material (cotton and polyester) and a cleanroom clothing system of polyester were evaluated in a dispersal chamber. The test confirmed that the source strength varies with clothing system and that the value of the source strength increases with the number of washing cycles.

- Whyte and Hejab (2007)
  A measurement study performed in a dispersal chamber showed that the source strength from a person wearing personal indoor clothing is in average 40 CFU/s and is about 3 CFU/s when the person is wearing a cleanroom clothing system.

- Ljungqvist et al (2012)
  Measurements performed in operating rooms during ongoing surgery showed that the source strength for a polyester clothing system of cleanroom quality was 0.5-0.9 CFU/s and for a clothing system of mixed material it was 4.6-6.2 CFU/s.

- Tammelin et al (2012)
  Presentation of a study performed in four operating rooms with dilution mixing air (0.76-1.05 m^3/s) and during ongoing orthopedic surgeries. The study compared three different clothing systems; one of mixed material (cotton/polyester) and two of polyester with different quality. The results showed that the source strength was 4.1 CFU/s for the clothing system of mixed material and 2.4 CFU/s and 0.6 CFU/s respectively for the clothing systems of polyester. The study showed that clothing systems made of polyester have a better protective capacity than those made of cotton/polyester.

- Kasina et al (2016)
  Comparison of three different clothing systems by measuring of airborne bacteria-carrying particles during ongoing surgery in operating rooms. The three different clothing systems were made of reusable mixed material (69% cotton, 30% polyester, 1% carbon fiber), reusable Olefin fabric (woven polypropylene) and disposable non-woven polypropylene. The study showed that the clothing system of single-use polypropylene reduced the amount of airborne bacteria-carrying particles during ongoing surgery in operating rooms significantly compared to the other two clothing systems.

4.4 Recommended Limit of Airborne Bacteria-Carrying Particles in Ultra Clean Air Operating Rooms

The correlation between microbiological cleanliness in the air in operating room and infection rate has been presented by Charnley (1972) and later confirmed by Lidwell et al (1982).

By summarize results from 5 800 total hip replacements between 1960 and the beginning of 1970, Charnley (1972) showed that the infection rate fell from 7 to 9 percent to approximately 1.5 percent mainly due to clean air. Further reduction of the infection rate down to 0.5 percent was believed based on the surgeon´s operating clothing system.

A multicenter study reported by Lidwell et al (1982) confirmed the result of Charnley´s summarization. 19 hospitals and over 8 000 operations were included in the study. All the operations were hip or knee joint replacement and the surgeons were allocated at random between conventional and ultraclean air operating rooms. The study showed that the incidence of deep sepsis after total joint replacement operations was reduced when the operations were performed in ultraclean air operating rooms. If the operating staff wore a special clothing system, i.e., a whole body-exhaust suite, further reduction was possible.

Whyte et al (1983) suggested that the air in the wound area maximum should on average, contain no more than 10 CFU/m^3, which today is an internationally accepted value for microbiological cleanliness in operating room for infection prone surgery.

5 MATHEMATICAL TREATMENT OF AIRBORNE CONTAMINANT CONCENTRATIONS

5.1 Introduction

The air may move in two different ways. One of these is characterized by a smooth flow, free of any disturbances, such as small and temporary vortices or eddies. This is known as laminar flow. The other type of flow is characterized by small and temporary fluctuations caused by instabilities. The flow velocity is no longer constant but more or less fluctuates around an average value. This is known as turbulent flow and the disturbances are often interpreted as being small temporary eddies.

In order to estimate the problems associated with transport of contaminants by air, understanding of how this transport occurs is needed. Based on traditional ventilation processes and applied rules, the assumption is that the air in the rooms is more or less turbulent.

The aim is to arrange ventilation in such a way that there is a certain basic flow of air. An organized basic flow implies that the flow can be characterized by means of streamlines, i.e., the paths taken by weightless particles in the room as they follow the air stream, if the turbulent fluctuations are ignored. The transport of contaminants due to the streamline flow is often described as convective transport.

The simplest system for an analysis of transport of contaminants by ventilation is, therefore, convective transport along the streamlines. The disturbances caused by turbulence (turbulent diffusion) are superimposed on this. Obviously, if there is no turbulence, turbulent diffusion is replaced by molecular diffusion or Brownian motion. It can generally be assumed, in regions with well-defined air flow fields

that the settling velocity of contaminants is negligible, which implies that the gravitation plays an inferior role.

In laminar flows gases and particles have different dispersion patterns, where the dispersion of gases is faster than that of particles. On the other hand, in turbulent flows due to the turbulence gases and particles have similar dispersion patterns, which are wider than that of laminar flows.

A vortex is characterized by the fact that the streamlines are closed within a region, which in the following is referred to as the vortex region. According to the laws of aerodynamics, tangential velocity in the vortex region should increase as the center of vortex is approached. However, systematic investigations by Ljungqvist (1979) show that this is not always the case in vortices formed in ventilated rooms. Everything indicates that the air mass within the vortex region moves as a rigid body under the influence of powerful turbulence. A certain amount of energy is, therefore, needed to maintain a vortex, and in most cases, this energy is obtained from the kinetic energy of the air on its entry into the room. The greater the kinetic energy of the air in the room, the greater the chance of the vortices occurring with closed streamlines.

Owing to the fact that the streamlines are closed, there is no convective removal of contaminants emitted within the vortex region. It is only turbulent diffusion within the vortex that causes removal of contaminants. In a room where contaminants are emitted within a vortex region, the average concentration of contaminants inside the vortex region can be 10 times higher than the air extracted by ventilation. This makes it possible to use the concept of contamination accumulation in the context of vortices.

It has also been shown by using illustrative methods that accumulation can occur in the wake caused by people or objects in a parallel flow provided that the contaminants are emitted in the wake region. Special consideration must be taken with instabilities and vortices generated by the working person.

The term contaminants has here reference to both airborne bacteria carrying particles, Colony Forming Units (CFU), and total number of airborne particles (viable and non-viable).

The risk of contamination does not only depend on the concentration of the contaminants, which is of critical importance, but also the motion of the contaminants. For a more thorough description of the interaction between air movements and dispersion of contaminants and contamination risks, see Ljungqvist and Reinmüller (1997, 2006, 2013).

5.2 Unidirectional Airflow

Dispersion from a fixed source in a uniform parallel flow is described theoretically and experimentally, inter alia by Bird et al (1960), Fuchs (1964), Hinze (1975), Ljungqvist (1979) and Ljungqvist and Reinmüller (2006). For continuous point source situated in the origin in a parallel flow with constant velocity v_0, in the *x*-direction, the concentration, *c*, after simplication becomes:

$$c = \frac{q}{4\pi Dx} \cdot e^{-\frac{v_0(y^2+z^2)}{4Dx}} \tag{5.1}$$

where q = outward particle flow from the point source (number/s)
v_0 = constant velocity in the *x*-direction (m/s)
D = diffusion coefficient (m^2/s)

The dispersion pattern in the *x*, *y* plane (*z=0*) is schematically shown in Figure 5.1.

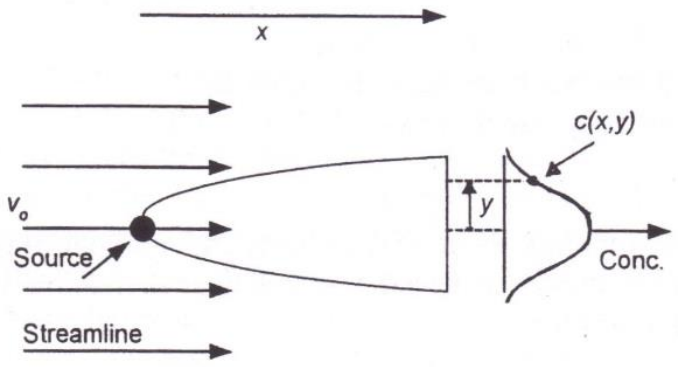


Figure 5.1 Schematically dispersion pattern caused by a continuous point source in a unidirectional flow with constant velocity in the x-direction.

The concentration for a continuous infinite line source situated along the *z*-axis with a strength q_l per unit length can in a simplified form be expressed as:

$$c = \frac{q_l}{2(\pi D v_0 x)^{1/2}} \cdot e^{-\frac{v_0 y^2}{4Dx}} \tag{5.2}$$

where q_l = outward particle flow per unit length from the line source (number/(s, m))

5.3 Dilution Mixing Airflow

With the assumption that the air movements in the operating room are dilution mixing, the doors are closed, and the concentration of airborne contaminants in the supply air has a constant value, an expression for the concentration in the operating room becomes:

$$\frac{dc}{dt} + \frac{(v_s A + Q)}{V} \cdot c = \frac{S + Q \cdot c_i}{V} \tag{5.3}$$

where
- c = concentration; bacteria-carrying particles (CFU/m^3), total number of particles (number/m^3)
- t = time (s)
- v_s = constant settling velocity (m/s)
- A = area of the room floor (m^2)
- Q = total air volume flow (m^3/s)
- S = total source strength in the room; bacteria-carrying particles (CFU/s), total number of particles (number/s)
- c_i = constant concentration in the supply air; bacteria-carrying particles (CFU/m^3), total number of particles (number/m^3)
- V = room volume (m^3)

Choose Q to the maximum value of either supply air or exhaust air and use this value in the numerical calculations.

The expression $v_s \cdot A \cdot c$ gives the number of particles deposited on areas equal to the floor area per unit time due to gravitational settling for a monodisperse aerosol.

The boundary condition is:

$c = c_0$ when $t \leq 0$

where c_0 = initial concentration; bacteria-carrying particles (CFU/m^3), total number of particles (number/m^3)

The expression of the concentration becomes:

$$c = \left(c_0 - \frac{(S + Qc_i)}{(v_s A + Q)}\right) e^{-\frac{(v_s A+Q)}{V} \cdot t} + \frac{(S + Qc_i)}{(v_s A + Q)} \qquad (5.4)$$

If there is no contaminants in the supply air, $c_i = 0$, Equation (5.4) becomes:

$$c = \left(c_0 - \frac{S}{(v_s A + Q)}\right) e^{-\frac{(v_s A+Q)}{V} \cdot t} + \frac{S}{(v_s A + Q)} \qquad (5.5)$$

It should be noted that Equation (5.4) and (5.5) only can be used for monodispersed aerosols (v_s = constant). For polydispersed aerosols the situation is more complicated.

The air movements depending on the activity during ongoing surgery have a decisive impact on the flow pattern and even the transport of contaminants, due to the upcoming air movements during activity that have velocities much higher than those depending on gravitational settling.

In order not to underestimate the concentration level during ongoing surgery the Equations (5.4) and (5.5) should preferably be used without the expression for gravitational settling, i.e., $v_s = 0$. This implies that the equations will be valid for polydispersed aerosols.

When gravitational settling is negligible, i.e., plays an inferior role, Equation (5.4) when $v_s A = 0$, becomes:

$$c = \left(c_0 - \frac{S}{Q} - c_i\right) e^{-\frac{Q}{V} \cdot t} + \frac{S}{Q} + c_i \tag{5.6}$$

When both the gravitational settling and the concentration in the supply air are neglected, i.e., $v_s A = 0$, and $c_i = 0$, the Equation (5.4) becomes:

$$c = \left(c_0 - \frac{S}{Q}\right) e^{-\frac{Q}{V} \cdot t} + \frac{S}{Q} \tag{5.7}$$

When the total source strength, *S*, only has reference to bacteria-carrying particles the contamination source mainly are the operating team and the following expression is valid:

$$S = n \cdot q_s \tag{5.8}$$

where n = number of persons present (number)
q_s = source strength, mean value of the number of bacteria carrying particles per second emitted from one person (CFU/s)

In the following airborne contaminants have reference to the operating team and its activities.

Case 1, Build up, ($c_0 = 0$, $S>0$)
When the operating team enters an empty room the initial concentration c_0 is assumed to be zero, the expression for concentration in Equation (5.7) becomes:

$$c = \frac{S}{Q}\left(1 - e^{-\frac{Q}{V}\cdot t}\right) \tag{5.9}$$

Case 2, Steady-state, ($t \rightarrow \infty$, $S>0$)
When the contaminant generation first starts, the concentration rises rapidly and then levels off. After sufficient time the exponential term exp(-*Q·t/V)* of Equation (5.9) and of Equation (5.7) approaches zero and the concentration asymptotically approaches a maximum steady-state concentration (c_{max}) given by:

$$c = c_{max} = \frac{S}{Q} \tag{5.10}$$

Case 3, Decay, (S = 0)
When the operating team leaves the operating room the contaminant generation stops. This can be calculated by setting the source strength to zero (*S = 0*) in Equation (5.7). The concentration becomes:

$$c = c_0 \cdot e^{-\frac{Q}{V}\cdot t} \tag{5.11}$$

where $c_0 = S/Q$

The expression *Q/V* is called the air change rate and is the inverted time constant of the room:

$$N = \frac{Q}{V} = \frac{1}{T} \tag{5.12}$$

where N = air change rate (1/s also 1/h)
T = time constant (s also min)

It should be noted that the concentration in steady-state only depends on the total source strength *S*, and the air volume flow *Q*, while the air change rate *Q/V* only has influence during increasing and decreasing concentration.

Equation (5.11) shows that the concentration decays exponentially with time. The decay time also called recovery time can with aid of Equations (5.11) and (5.12) be expressed as:

$$t = T \ln \frac{c_0}{c} \tag{5.13}$$

According to ISO 14644-3 Test methods (2005) and SIS TS 39:2015 (2015) cleanliness recovery performance is evaluated by using the 100:1 recovery time, which is defined as the time required for decreasing the initial concentration by a factor of 0.01.

For example, two operating rooms with dilution mixing air and air change rates of 20 changes per hour and 15 changes per hour respectively, will get the following theoretical recovery times:

20 air changes per hour (*T = 3* min) gives 13.8 minutes

15 air changes per hour (*T = 4* min) gives 18.4 minutes

Figure 5.2 illustrates the principal graphs of cases 1-3 (build-up, steady-state, decay) in form of dimensionless concentration in an operating room with 20 air changes per hour (ach/h). The dimensionless concentration is described, as the quotient between concentration and the maximum concentration.

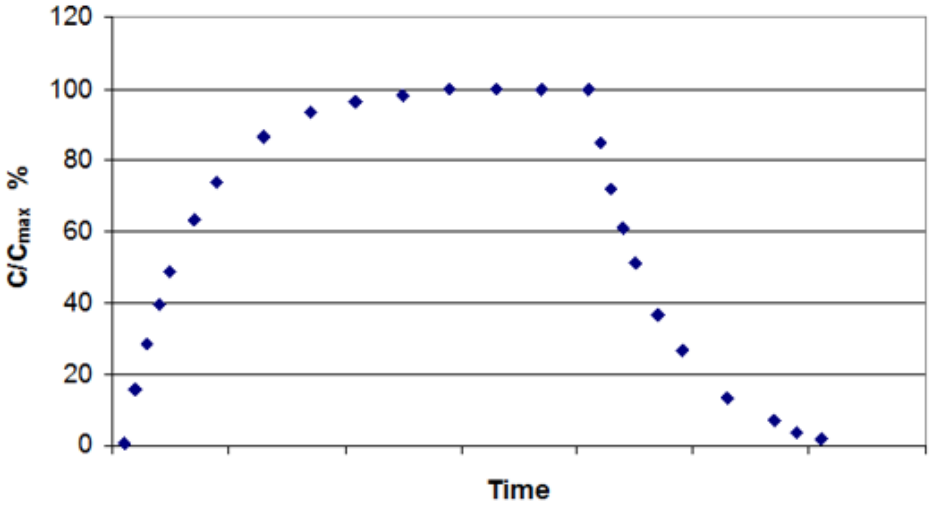


Figure 5.2 The principal graphs of cases 1-3 (build-up, steady-state, decay). The dimensionless concentration (the quotient between concentration and the max concentration) as function of time in an operating room with 20 ach/h.

5.4 Common Application of Viable Particles

A commonly used application of viable particles is Equation (5.14) where the motion of particles only depends on the settling velocity. When an equivalent mean diameter of bacteria-carrying particles can be established, the settling velocity becomes a constant value. If the concentration of bacteria-carrying particles in the air, the area of exposed surface, and the exposure time are known, the number of bacteria-carrying particles deposited can be calculated. When the concentration of bacteria-carrying particles is uniformly distributed and constant during exposure time, the expression for the number of particles deposited, N_d, is:

$$N_d = v_s \cdot c_b \cdot A_e \cdot t_{exp} \tag{5.14}$$

where c_b = concentration of bacteria-carrying particles (number/m^3)
A_e = area of exposed surface (m^2)
t_{exp} = exposure time (s)

With the assumption, according to Whyte (1986), that the average size of bacteria-carrying particle is 12 micron, the settling velocity will be $0.462 \cdot 10^{-2}$m/s. The concentration in bacteria-carrying particles will yield the expression:

$$c_b = \frac{N_d}{0.462 \cdot 10^{-2} \cdot A_e \cdot t_{exp}} \tag{5.15}$$

With a settle plate of 140mm diameter and 1 hour exposure time the concentration of bacteria-carrying particles in Equation (5.15) expressed in Colony Forming Units per m^3 (CFU/m^3) becomes:

$$c_b = 3.9 \cdot N_d \tag{5.16}$$

For example, passive sampling of air in areas with the demand of maximum 100 CFU/m^3 the number of colonies is about 26 according to Equation (5.16). This value can be compared to the value of 30 colonies given in SIS-TS39:2015 (2015).

A SAR-value (surface/air ratio) is described by Friberg (1998). This value gives the number of bacteria-carrying particles which are deposited during one hour (3600s) on a unit of 1m^2 (65 agar plates with a diameter of 14cm) divided by the concentration of airborne bacteria-carrying particles.

With Equation (5.15) the theoretical SAR-value (N_d/c_b) can for dilution mixing air be estimated to 16.6. This value agrees with results from measurements performed in operating rooms with dilution mixing air described by Friberg (1998).

5.5 Door Openings

Airflow through doorways

Airflow through doorways are discussed in several papers, see Shaw and Whyte (1974), Kiel and Wilson (1989), Wilson and Kiel (1990), Isfält et al (1996), Ljungqvist et al (1997, 1998a, 2006, 2009), Schulz (2001), Blomqvist (2009) and Ullmann (2011). The driving mechanisms for air flows are typically a combination of density differences, mechanical ventilation, motion of a person through the opening and the motion of the door itself. In most practical situations, the density differences are caused by temperature differences.

When small temperature differences occur, the air flow through doorways can be estimated only approximately from the relationship describing density driven flow. At higher temperature differences (>4°C) the estimation will be more accurate. The theoretical velocity profile through a doorway with temperature differences is schematically shown in Figure 5.3.

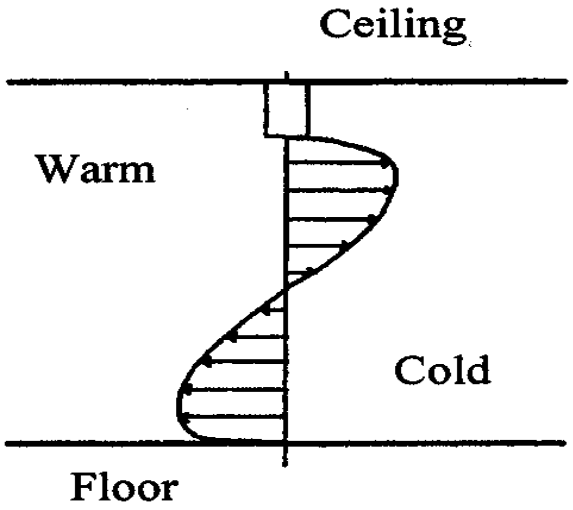


Figure 5.3 Schematic representation of the theoretical velocity profile through a doorway with a temperature difference.

Through one-half of the opening, the discharge flow rate, Q_d, (m^3/s), in each direction can be calculated with the following equation:

$$Q_d = C_d \frac{WH^{3/2}}{3} \left(g \frac{\Delta \rho_o}{\rho_{om}} \right)^{1/2} \tag{5.17}$$

where
C_d = discharge coefficient
W = opening width (m)
H = opening height (m)
g = gravitational acceleration (m/s^2)
$\Delta \rho_o$ = density difference (kg/m^3)
ρ_{om} = mean density (kg/m^3)

Fritzsche and Lilienblum (1968), Kiel and Wilson (1989), and Wilson and Kiel (1990) have reported that the discharge coefficient is dependent upon the temperature difference between the rooms. For large temperature differences (40°C-80°C), the value of the coefficient C_d increases from about 0.6 to 0.8, but for small temperature differences (i.e., less than 10°C) the value is in a range about 0.45. This value should be compared with the experimentally estimated value of 0.8, given by Shaw and Whyte (1974), for temperature differentials of around 1-10°C.

Etheridge and Sandberg (1996) give a review of flow through large openings where theoretical models and experimental results are described. Values of the coefficient C_d are given in the range 0.4-0.8. A value about 0.65 has been taken by various sources for door opening and is in agreement with theoretical considerations.

With the aid of the equation of state for ideal gas, the density relation in Equation (5.17) can be expressed as a function of temperature:

$$\frac{\Delta\rho_o}{\rho_{om}} = \frac{2\Delta T}{(T_1 + T_o)} \tag{5.18}$$

where ΔT = temperature difference (K)
T_1 = temperature (K)
T_0 = reference temperature (K)

Graphical representations of Equation (5.17) with C_d = 0.8 in combination with Equation (5.18) expressed in flow rate as a function of temperature difference and opening dimensions are shown in Figure 5.4 (increasing temperature) and Figure 5.5 (decreasing temperature). The reference temperature (0 in diagrams) is chosen to normal room temperature 20°C (293K).

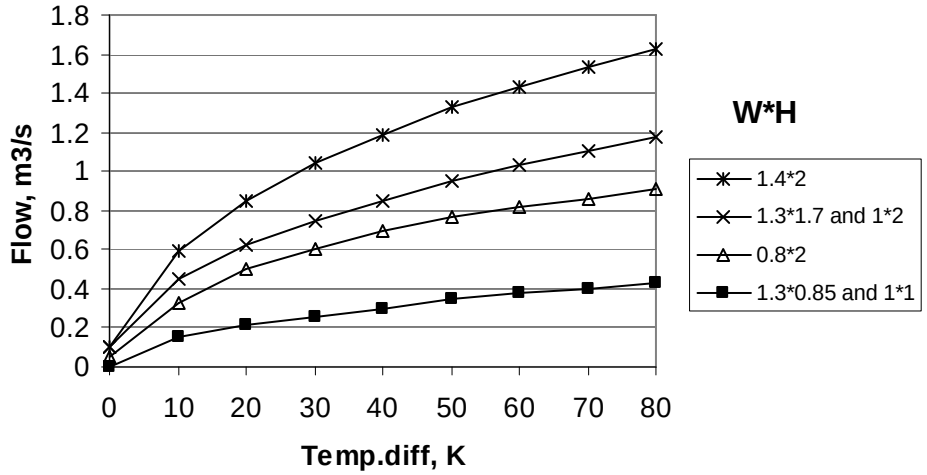


Figure 5.4 Flow rate as a function of temperature difference (increasing temperature with ref. temp. 20°C) and opening dimensions (width W and height H in m) when C_d = 0.8.

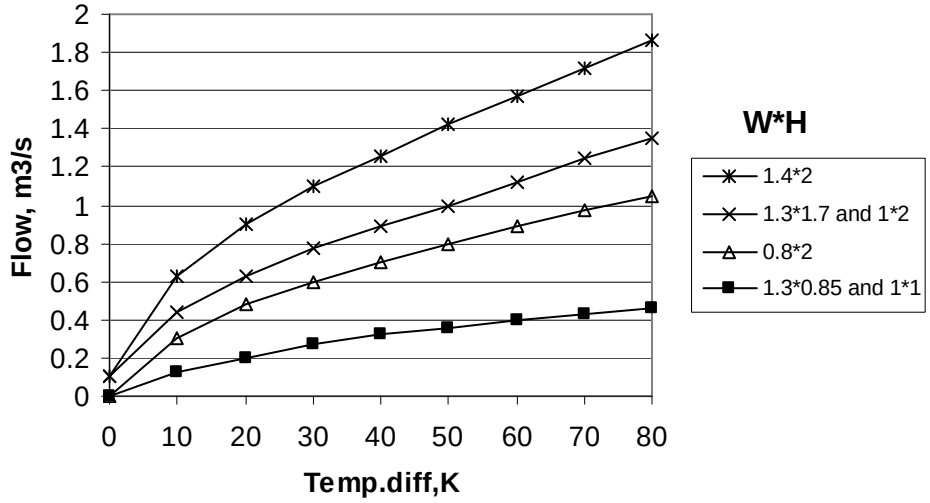


Figure 5.5 Flow rate as a function of temperature difference (decreasing temperature with ref. temp. 20°C) and opening dimensions (width W and height H in m) when C_d = 0.8.

Equivalent opening time

The flow rate in Equation (5.17) applies to an opening of fixed dimensions at a time when steady flow is fully established. In the case of an opening and closing door the flow rate will be reduced. To compensate this Ljungqvist et al (2009) describe an equivalent opening time which should be used when concentrations of airborne contaminants are calculated influenced by open doorways. The expression for the equivalent time t_e, will, with constant value of the discharge coefficient and when the door swing speed is constant, be:

$$t_e = t_h \sin\theta_0 + \frac{t_0 + t_c}{\theta_0}(1 - \cos\theta_0) \qquad (5.19)$$

where t_h = open hold time (s)
t_0 = opening time (s)
t_c = closing time (s)
Θ_0 = max. opening angle (rad)

For example, if the maximum door opening angle is π/2, the expression for the equivalent time, t_e, becomes:

$$t_e = t_h + \frac{2}{\pi}(t_0 + t_c) \tag{5.20}$$

It could be mentioned that a sliding door moving at a constant velocity would result in a factor of 0.5 rather than 2/π in Equation (5.20).

Concentration of airborne contaminants in a chamber

When temperature differences exist between the controlled environment and the chamber of the autoclave or the freeze-dryer during loading and unloading contamination risks occur.

With the assumption that the discharge flow rates through the door opening in each direction have the same value when the chamber door is open, the air movements in the room and in the chamber with open door are turbulent mixing, and the airborne contaminants in the room has a constant level, an expression for the concentration in the chamber becomes

$$\frac{dc}{dt} + \frac{Q_d}{V_c}c = \frac{Q_d c_R}{V_c} \tag{5.21}$$

where V_c = chamber volume (m^3)
c_R = constant concentration in the room (ambient area); bacteria-carrying particles (CFU/m^3), total number of particles (number/m^3)

The boundary condition is $c = 0$ when $t \leq 0$.

The expression of the concentration in the chamber when the door is open becomes

$$c = c_R \left(1 - e^{-\frac{Q}{V_c} t} \right) \tag{5.22}$$

Autoclaves and freeze dryers can have temperature differences to surrounding area of 50°C and 40°C respectively and the chamber volumes can vary from 1m^3 to 8m^3. With the assumption of a discharge coefficient in the range of 0.6-0.8, which is in agreement with the references described in part Airflow through doorways, the value of *Q/V* will become between 0.1 to 0.35 with above given data.

With Equation (5.22) the concentration as a function of time can be estimated when the chamber door is opened, see Figure 5.6.

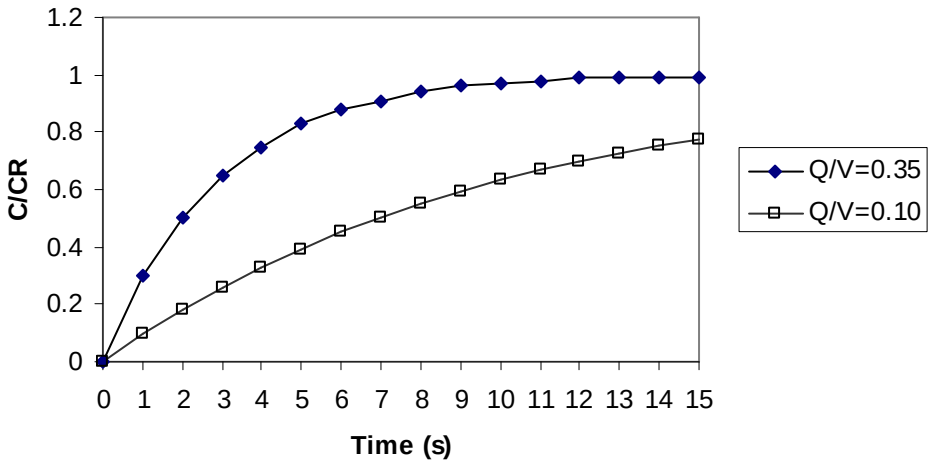


Figure 5.6 Concentration related to the concentration in the room (c_R) as a function of time in a chamber of an autoclave or a freeze dryer, when the door is opened and the temperature differences to surrounding area are 40-50°C (C_d = 0.6-0.8).

The concentration curve in Figure 5.6 applies to a fully opened chamber door (opening angle of $\pi/2$). If the concentration during the opening time shall be estimated, the equivalent time for opening should be considered, see Equation (5.20).

Studies have shown that the opening time is about 3-5 seconds, which give with an equivalent time for opening of 2-3 seconds. During the opening time the chamber concentration can become between 20-65 percent of the concentration in the room, see Figure 5.6. This theoretical discussion is valid when there are no HEPA-filter units above the autoclaves and the freeze dryers.

Concentration of airborne contaminants in an operating room when the door is open

The mathematical expressions for concentration of airborne contaminants in an operating room when the door is open have been described by Ljungqvist et al (2009) and calculations have been performed by Nordenadler (2010).

Here airborne contaminants have reference to bacteria-carrying particles, also called Colony Forming Units (CFU).

With the assumption that:

- the air movements in the operating room and the ambient area (corridor) are turbulent mixing
- supply air is HEPA filtered
- the discharge flow rates through the door opening in each direction have the same value when the door between the operating room and the corridor is open
- the total source strength is constant
- the concentration of airborne contaminants in the corridor has a constant level

an expression for the concentration, *c*, in the operating room when the door is open becomes:

$$c = \left(c_0 - \frac{S}{(Q_d + Q)} - \frac{Q_d \cdot c_c}{(Q_d + Q)}\right) \cdot e^{-\frac{(Q_d+Q)\cdot t}{V}} + \frac{S}{(Q_d + Q)} + \frac{Q_d \cdot c_c}{(Q_d + Q)} \qquad (5.23)$$

where c_c = constant concentration of bacteria-carrying particles in the corridor (ambient area) (CFU/m^3)

When the door is closed there is no flow rate through the door opening, i.e., Q_d is 0, and the expression (compare Equation (5.7)) becomes:

$$c = \left(c_0 - \frac{S}{Q}\right) \cdot e^{-\frac{Q}{V}\cdot t} + \frac{S}{Q} \qquad (5.24)$$

If there is a different number of persons in the operating room after the door is closed than before the door is opened, a correction of total source strength *S* and the concentration c_0 should be performed. The air volume flow due to mechanical ventilation, *Q*, should always be the maximum air flow through the operating room.

When the door is open only for a short time period the concentration reduced by the air volume flow through the mechanical ventilation system could be neglected. This gives the following approximate expression:

$$c = c_0 + \frac{Q_d \cdot t_e \cdot (c_c - c_0)}{V} \qquad (5.25)$$

The equivalent time, t_e, is dependent on opening time, open hold time, closing time and maximum door opening angle, see Equation

(5.19). For a sliding door a modification of Equation (5.19) should be used.

At a temperature difference of zero between rooms, the typical exchange volume when door is moving, is about 50% of the swept volume of the door. With the same assumptions as in Equation (5.25) an approximate expression becomes:

$$c = c_0 + \frac{V_d}{V} c_c \qquad (5.26)$$

where V_d = air volume pumped by moving door (50% of the swept volume of the door) (m^3)

It should be noted that the concentrations expressed in Equation (5.25) and Equation (5.26) only give estimations of occurring maximum levels due to concentration reduction when the air volume flow through the mechanical ventilation system is neglected.

In general, the number of door openings should be a minimum and the door open hold time should be as short as possible, i.e., the equivalent door opening time should be minimized.

6 MATERIAL AND METHODS

6.1 Autoclaves

Background

In sterile supply centers autoclaves are used for sterilization of instruments and equipment. Generally, there is a temperature difference between the air in the room and the autoclave chamber when the autoclave is opened after a process run. This can cause a flow of room air through the opening and may create a contamination risk. To minimize the risk, a HEPA-filter unit can be installed above or beside the chamber opening of autoclaves to provide clean air and thus protect the opening. The airflow needed through the HEPA-filter unit depends mainly on the temperature difference between the chamber and the room and the size of the chamber opening. The flow of clean air from the HEPA-filter unit should be greater than that of the theoretically calculated flow through the chamber opening in order to minimize contamination risks.

Purpose

The purpose of the study was to increase the understanding of air movements and the dispersion of contaminants in autoclaves when doors to such equipment are open and establish a basis for dimensioning the HEPA-filter unit required for protection of the opening. The study also included a risk assessment with purpose to investigate risk situations caused by airflows through the chamber opening of the autoclave when chamber door is open.

Mapping of air movements, air velocities and temperatures

Material

Autoclave

The investigation was performed at an autoclave located in a laboratory room, see Figure 6.1. The laboratory room was an unclassified area. The dimension of the chamber opening of the autoclave was 0.7m x 0.7m and the chamber depth was 0.92m. The distance from the floor to the chamber opening lower edge was 0.77m.

The chamber opening of autoclaves can be either down to the floor or further up. While the autoclave for the test had its opening further up, a floor was simulated to create an autoclave with its opening down to floor. By placing a table against the lower edge of the opening, see Figure 6.2, an autoclave with its opening down to the floor was simulated. This solution made it possible to perform tests and evaluate results between autoclaves with different opening arrangements.

Figure 6.1 View of the laboratory room with the investigated autoclave.

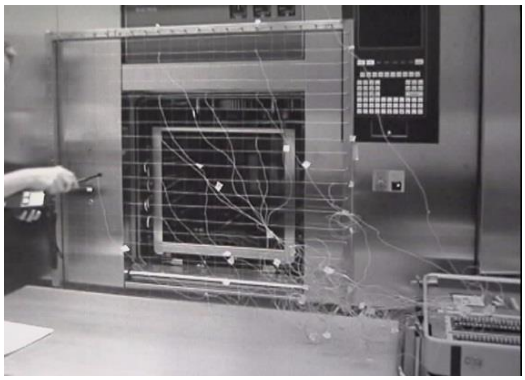


Figure 6.2 The arrangement with a table to simulate an autoclave with its chamber opening down to the floor.

Four different cases and conditions for the autoclave were studied, see Table 6.1.

Table 6.1 The four different cases and their respective conditions for the autoclave.

Case	Conditions
1	Autoclave with empty chamber. The distance from the floor to the chamber opening lower edge is 0.77m.
2	Autoclave with load (weight 34kg) in the chamber. The distance from the floor to the chamber opening lower edge is 0.77m.
3	Autoclave with empty chamber. The chamber opening is down to the floor (raised floor simulated by using a table).
4	Autoclave with load (weight 34kg) in the chamber. The chamber opening is down to the floor (raised floor simulated by using a table).

Measurement equipment
The equipment used for the different measurements, see Table 6.2.

Table 6.2 Equipment in the different measurements.

Measurement	Equipment
Air movements	Air current tubes (Dräger CH 216)
Air velocity	A hotwire anemometer
Temperature	Thermo-couples

Method

The study consisted of series of measurements in front of the opening of an autoclave. During all tests there were temperature differences between the air in the room and the air in autoclave chamber.

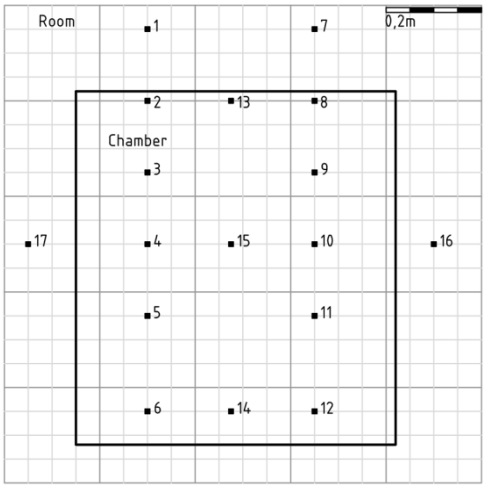
The time for the measurement was approx. 30 minutes for each test and started at the end of a process cycle when the door to the autoclave was opened.

In order to see if different conditions would affect the results, four different cases were studied, see Table 6.1. Each case consisted of four tests.

During all studies the temperature of the air in the autoclave chamber was above the air temperature in the laboratory room. The air temperature in the laboratory room was about 25°C. The temperature in the chamber of the autoclave was about 105°C when the door to the chamber was opened after a process cycle. This means that the temperature difference between the air in the chamber and the laboratory room was about 80°C at the beginning of the measurements.

Visualization of air movements
To visualize the air movements in front of the chamber opening of the autoclave, the smoke was released at different locations in order to visualize the main air movements. The visualization started when the door to the chamber was open and was repeated four times during the time for each study.

Air velocities
The air velocity was measured in a vertical grid in front of the opening of the autoclave, see Figures 6.3. The registration of the air velocities was made in the vertical grid with two different distances from the chamber opening. The first registration was made about 5 cm from the chamber opening and the second registration was made about 30-50cm from the opening. These two different registrations were repeated four times during the time for each test.



One square length is equivalent to 0.05m. The bold line shows the chamber opening.

Figure 6.3 The grid for the registration of the air velocities in front of the opening of the autoclave.

Air temperatures
The air temperatures were registered in a vertical grid in front of the opening (approx. 5cm from the chamber opening). The vertical grid for the locations of the thermo-couples were the same as the vertical grid for the registrations of the air velocities, see Figures 6.3.

The distances between the measuring points in the grid distance was 15-17.5cm.

Eighteen thermo-couples were used. Thermo-couple number eighteen was placed in the chamber.

Risk Assessment

Material

Autoclave

The investigation was performed on an autoclave located in a laboratory room. The laboratory room was an unclassified area. The dimension of the chamber opening of the autoclave was 0.7m x 0.7m and the chamber depth was 1.3m. A table was placed against the lower edge of the opening to simulate an autoclave with its opening down to the floor. The temperature difference between the air in the chamber and the ambient room air was about 50-60°C. The room air was about 20°C. Five different cases and conditions for the autoclave were studied, see Table 6.3 and Figures 6.4 and 6.5. One test was performed for each case.

Table 6.3 The cases and their respective conditions for the autoclave.

Case	Condition
1	The autoclave with no UDF-unit.
2	The autoclave with a UDF-unit with horizontal airflow installed on the side of the chamber opening covering about 2/3 of the lower part of the opening (see Figure 6.4). The velocity of the air flow from the UDF-unit was in average about 0.45m/s.
3	The autoclave with a UDF-unit with horizontal airflow installed on the side of the chamber opening covering about 2/3 of the lower part of the opening (see Figure 6.4). The velocity of the air flow from the UDF-unit was in average about 0.65m/s.
4	The autoclave with a UDF-unit with horizontal airflow installed on the side of the chamber opening covering about 2/3 of the lower part of the opening (see Figure 6.4). The velocity of the air flow from the UDF-unit was in average about 1.0m/s.
5	The autoclave with a UDF-unit with horizontal airflow installed on the side of the chamber opening covering the opening and additional 15cm above the opening (see Figure 6.5). The velocity of the air flow from the UDF-unit was in average about 1.0m/s.

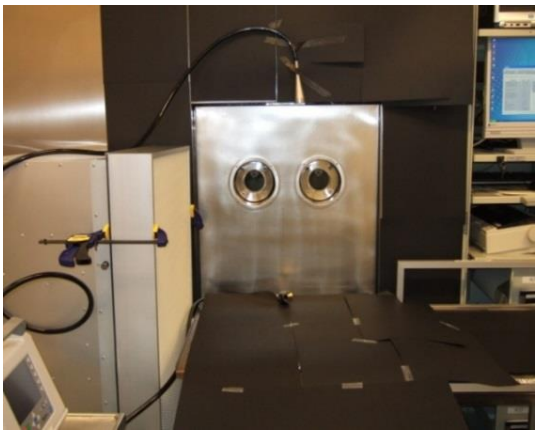


Figure 6.4 Cases 2-4: UDF unit covering about 2/3 of the chamber door of the autoclave with horizontal airflow.

Figure 6.5 Case 5: UDF unit covering the chamber opening of the autoclave and additional 15cm above the opening with horizontal airflow.

Measurement equipment

The equipment used for the different measurements, see Table 6.4.

Table 6.4 Equipment used in the different measurements.

Measurement	Equipment
Air movements	Air current tubes (Dräger CH 216)
Air velocity	A hotwire anemometer

Method

The risk assessments were, when the autoclave chamber door is open, performed with and without UDF-units, and carried out with the method of limitation of risks - LR-method.

The LR-method was developed by Ljungqvist and Reinmüller (1993, 1995, 2006) and is a reliable method for evaluation of microbial safety. The method is an engineering tool and is useful in the work of risk assessment. By using the method, it is possible to get information about weak links and establish critical control points. By using the results from visualization of air movements and particle challenge tests, calculations of risk factors can be performed. The value of the calculated risk factor makes it possible to identify where risk situations occur. The study should be performed during simulated production activity.

Short description of the LR-method:

- Visualization of the air movements in order to identify critical vortices or turbulent regions in the clean zone.
- The challenge test; a particle counter probe is placed in the critical area and during measurement particles are generated in the surrounding air. The generated particles should be more than 300,000 particles of 0.5µm or larger per cubic foot.
- Estimation of the risk by calculating a risk factor. The definition of the risk factor is the ratio between measured particle concentrations in the critical area to the generated concentration of particles in the ambient air. If the result gives a risk factor value less than 10^{-4} (0.01%), there should be no microbiological contamination from the air in the process during ordinary manufacturing condition according to Ljungqvist and Reinmüller (1993, 1995, 2006).

During all tests there were temperature differences between the air in the room and the air in the chamber of the autoclave. The time for the measurements was approx. 30 minutes for each test and started

at the end of a process cycle when the door to the autoclave was opened.

Five different conditions were studied for the autoclave, see Table 6.3. For all the different conditions, four different challenge tests (challenge area) were performed, see Table 6.5 and Figures 6.6 and 6.7.

Table 6.5 *Challenge areas during tests of the autoclave.*

G1	Particle generation in the room.
G2	Particle generation just outside the UDF-unit area.
G3	Simulating loading/unloading of the autoclave. Particles are emitted only from a person dressed in a coat used for laboratory work.
G4	Particle generated in the UDF-unit area.

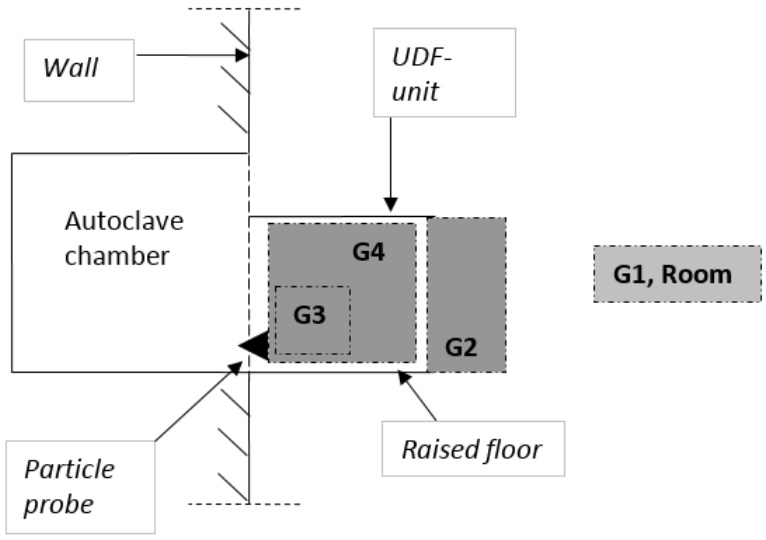


Figure 6.6 Side view of the autoclave and the challenge areas G1-G4.

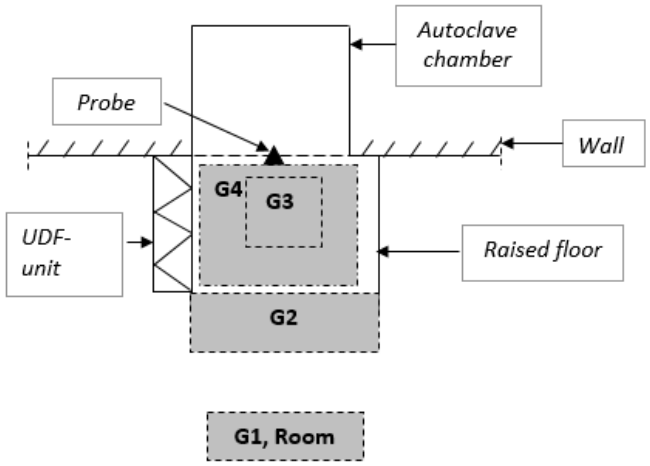


Figure 6.7 Plan view of the autoclave and the challenge areas G1-G4.

The smoke was released at different locations in front of the chamber opening of the autoclave in order to visualize the main air movements.

The particle probe was placed in the inflow of the autoclave, see Figure 6.8.

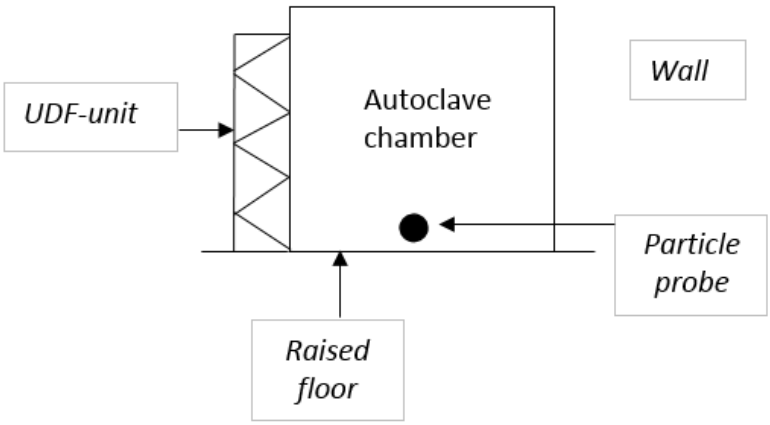


Figure 6.8 Front view of the autoclave and the location of the particle probe.

Computer Model

Material

The risk situations depend on the entrainment of room air into the loading chambers. Air movements, air velocities and temperature gradients play here a vital rule. A computer model was created with the use of Computational Fluid Dynamics (CFD) in order to study the air movements, the air velocities and the temperature gradients for five different cases for an autoclave, see Table 6.6. The temperature difference between the air in the autoclave chamber and the ambient air was 80°C for all the different cases.

Table 6.6 The different cases and their conditions for the fictitious autoclave.

Case	Condition
1	The autoclave with no UDF-unit (see Figure 6.9).
2	The autoclave with a UDF-unit installed above the opening(see Figure 6.10). The air velocity of the airflow (vertical flow) from the UDF-unit was 0.45m/s.
3	The autoclave with a UDF-unit installed above the opening(see Figure 6.10). The velocity of the airflow (vertical flow) from the UDF-unit was 0.90m/s.
4	The autoclave with a UDF-unit installed on the side of the opening(see Figure 6.11). The velocity of the airflow (horizontal flow) from the UDF-unit was 0.45m/s.
5	The autoclave with a UDF-unit installed on the side of the opening(see Figure 6.11). The velocity of the airflow (horizontal flow) from the UDF-unit was 0.90m/s.

The fictitious autoclave had a chamber opening of 0.7m x 0.7m and a chamber depth of 1.3m. The UDF unit installed above the opening, cases 2 and 3, had a size of 0.6m x 0.7m. In case 4 and 5, where the UDF-unit was placed on the side of the chamber opening, the size was 0.6m x 0.8m. The autoclave was placed in a room of size 6m x 5m x 3m. The fictitious room was provided with ventilation; four air inlets were placed in the ceiling and two exhaust devices were placed low in the walls. The size of the air inlets was 0.6m x 0.6 m and the exhaust devices were 0.3m x 0.4m. The air change rate in the room was set to 20 air changes per hour.

The performance of each case see Figures 6.9 – 6.11.

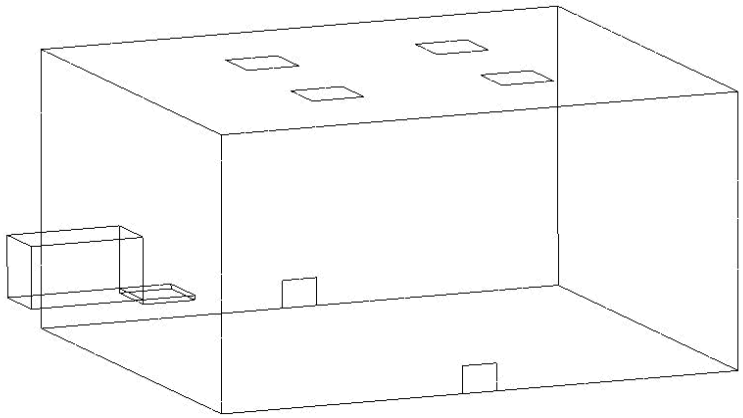


Figure 6.9 Case 1: View of the fictitious room and the autoclave.

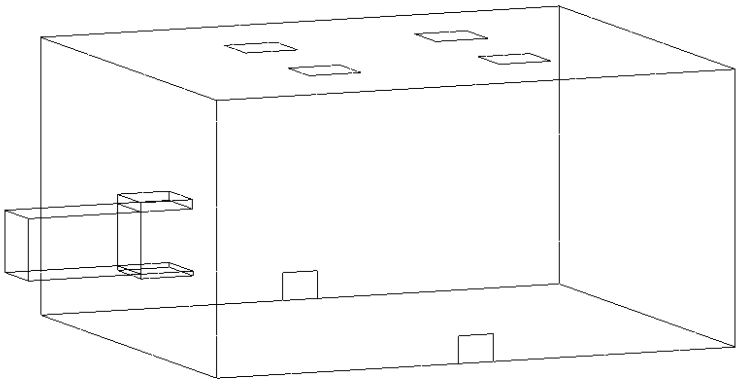


Figure 6.10 Cases 2 and 3. View of the fictitious room and the autoclave with a UDF-unit above its opening.

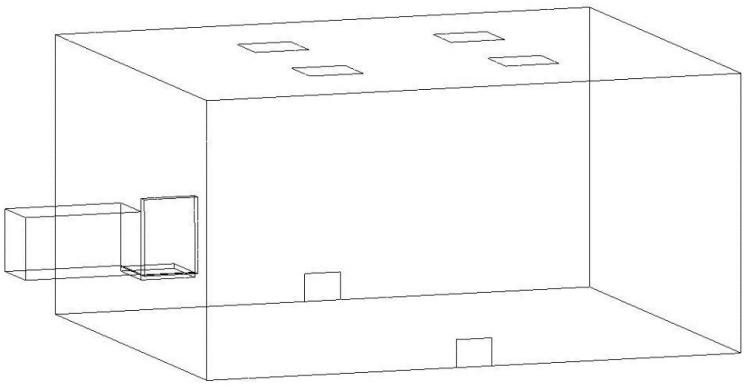


Figure 6.11 Cases 4 and 5: View of the fictitious room and the autoclave with a UDF-unit on the side of the opening.

Method

In a general CFD evaluation of a scenario there are three main steps: pre-processing, solver-execution and post-processing. The pre-processing stage refers to the creation of a geometry and computational grid. Boundary conditions of the fluid region and control volumes are also constructed and defined in this stage. All computer calculations take place in the solver-execution stage and the results derive from the solution of the governing equations for a specific problem. The final step is post-processing, which consists of examining and interpreting the graphical representation of the results and the findings from the simulations.

The computer software in this analysis was Fluent®. Fluent® uses the Finite Volume Method to solve the governing equations. In the finite volume method, the fluid domain is divided into a finite set of discrete control volumes. This is done by dividing the fluid domain into a finite set of nodal points where the surroundings of each nodal point represent a control volume. The control volumes facing the fluid domain boundaries are given boundary conditions according to the specific problems.

The boundary conditions (BC) for the fluid region and control volumes were defined and all surfaces encapsulating the fluid region were given specific boundary conditions. In Fluent® this is done by geometrically identifying different zones as inlet, outlet, wall etc.

Figures 6.12 and 6.13 illustrate the boundary zones (Zone 1 – Zone 6) encapsulating the fluid region with respective boundary condition.

BC Zone 1: Surfaces in the ceiling for supply air openings were defined as velocity inlets.

BC Zone 2: Small surfaces on the adjacent walls define exhaust air outlets.

BC Zone 3: Inlet (protection) air from HEPA filter unit.

BC Zone 4: Return (recirculated) air to HEPA filter unit.

BC Zone 5: The walls of the autoclave where designed as solid surfaces with a fixed temperature to represent the objects high thermal mass.

BC Zone 6: Internal cell zone representing the air in the autoclave. Initial condition of the temperature of the air was set to 80°C (353 K).

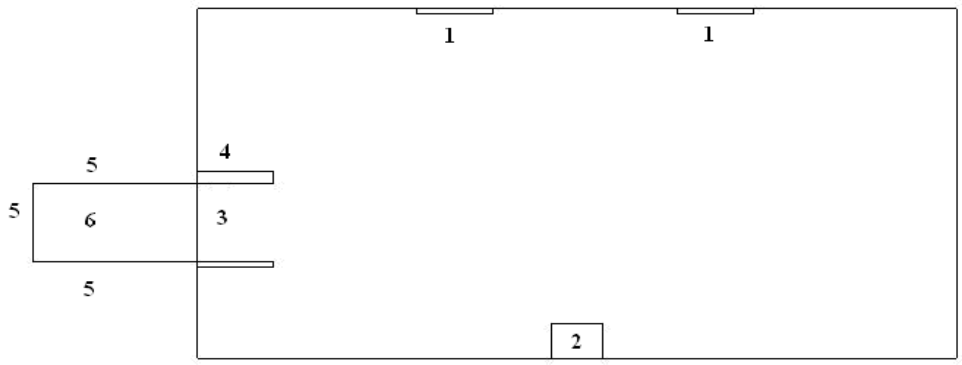


Figure 6.12 Side view room with given boundary zones.

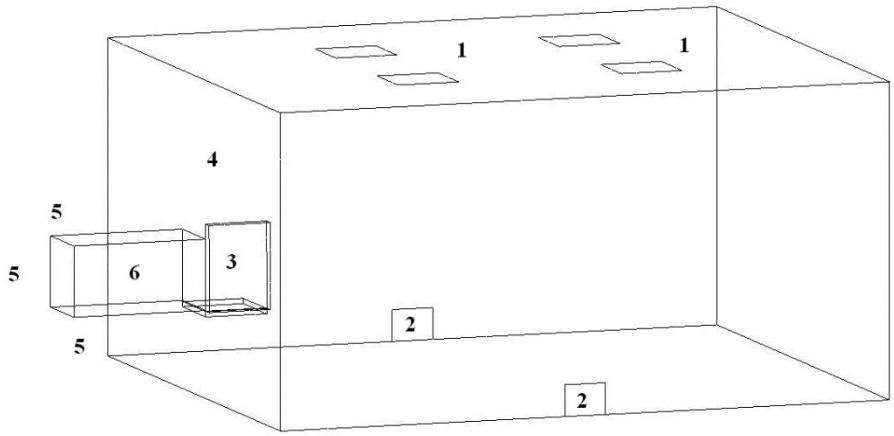


Figure 6.13 View of the room with given boundary zones.

The air is assumed to be incompressible and the airflow field was achieved from the solution of the transient Navier-Stokes Equations. The turbulence in the flow was modeled using the unsteady standard k-ε model.

6.2 Contamination of the Outside Surface of Clothing Systems

Background

In operating rooms used for orthopedic surgery, the personnel wear clothing systems suitable for ultraclean air environments. The procedure for the change of surgical clothing system for personnel working within an orthopedic surgery department varies between different hospitals. Some orthopedic surgery departments require personnel to change their clothing system between every surgery, while personnel in other orthopedic surgery departments wear the same surgical clothing system during a complete working day/shift.

The main source for microbial contamination in an operating room is normally the personnel and the patient, and the level of airborne bacteria-carrying particles in the operating room for orthopedic surgery is considered an indicator of the risk of patient infections.

Purpose

The purpose of this study was to investigate the microbial contamination risks of the outside surface of the surgical clothing system during a day of use and to determine if there is a higher risk of microbial contamination of the clothing surface if personnel visit uncontrolled areas outside the surgical department.

To determine if the intended microbial sampling method for the observational study in the orthopedic surgical department was a reliable measurement method, a pre-study was performed on a test dummy to validate the test method, see also Jordestedt (2015) and Ullmann et al (2017a).

Material

Surgical clothing system

The surgical clothing system used in this study was a disposable surgical clothing system of non-woven material. The reason for the chosen surgical clothing system is based on the possibility of separating the contamination from the environment and the users' skin.

The fabric is antistatic-treated, and the material is made of spun bonded polypropylene (50g/m^2). The clothing system consists of a short-sleeved shirt and a trouser, see Figure 6.14. There are cuffs at the end of the arms, legs and waist. The clothing system was stored in plastic bags until donning but was not sterilized before use.

Figure 6.14 The surgical disposable clothing system.

Microbial sampling material

For microbial sampling contact plates of type RODAC (Replicate Organism Detection And Counting) were used, see Figure 6.15. The microbial growth medium was standard medium Tryptic Soy Agar (TSA) in 55-mm Petri dishes. The sampling plates were gamma-irradiated and delivered in a triple-wrapped package. After performed sampling the contact plates were incubated. The incubation was not less than three days at 32°C followed by not less than two days at room temperature.

The number of CFU (Colony-Forming Units) were counted and recorded as CFU/plates, i.e., CFU/24cm^2.

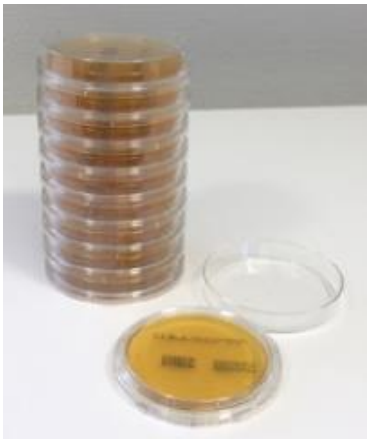


Figure 6.15 Contact plates of type RODAC.

Premises for the orthopedic surgical department

The surgical department, where the study on personnel was performed, includes the following facilities:

- preoperative transfer
- operating rooms with anterooms (the majority of the operating rooms are located in the center of the department)
- support areas such as sterile storage, medicinal storage, washing rooms and offices
- changing room and staffroom with kitchen

The surgical personnel and the patients use the anterooms as an entrance to the operating rooms. A department with recovery rooms is connected to the surgical department.

Figure 6.16 shows a schematic drawing of the surgical department which has three different entrances:

Entrance 1: The locker rooms for personnel are located on the floor above the surgical department. By using a stairwell and an elevator the personnel reach the department through this entrance.

Entrance 2: The surgical personnel are using this entrance to reach the staffroom during the working day.

Entrance 3: This entrance is used for patients.

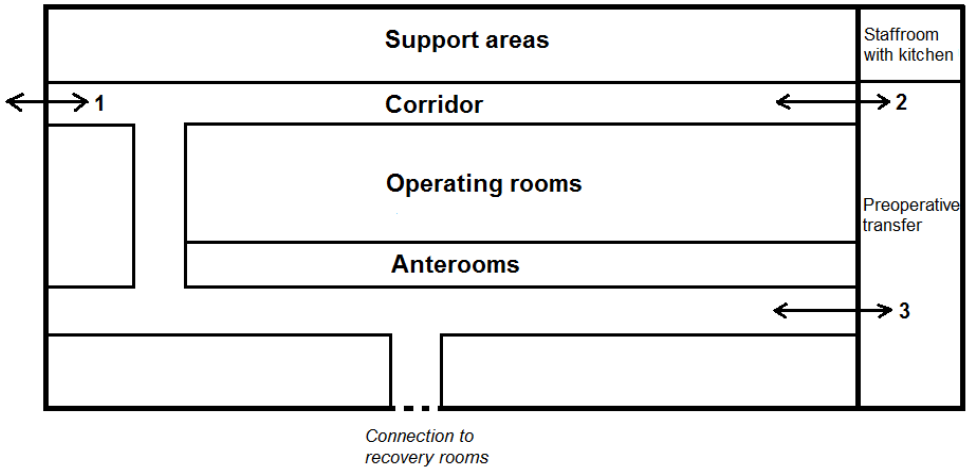


Figure 6.16 Schematic drawing of the surgical department.

Test persons

The test covered persons with three different professional responsibilities; nurse, surgical nurse and anesthesia nurse. Most of the test subjects were female; 12 female and 1 male.

Method

The study was performed in two steps; a pre-study to validate the microbial sampling method and a main study on personnel at an orthopedic surgical department.

Validation of the microbial sampling method

Before the performance of the main study on personnel at an orthopedic surgical department, the microbial sampling method needed to be validated as a reliable measurement method. The validation was performed by using a test dummy wearing the surgical clothing system and exposing the dummy and the surgical clothing system in a public environment (a lunch restaurant) at Chalmers University of Technology. Simultaneously with the test on the dummy, the exposure was performed on a test person wearing the same surgical clothing system. Figure 6.17 shows the test person and the dummy during the exposure in the public environment.

Figure 6.17 The test person and the dummy during the exposure in the lunch restaurant. (Photo B. Reinmüller in Jordestedt (2015)).

The validation test consisted of the following four steps:

1. In a separate room the test person and the dummy were dressed in the surgical clothing system including a surgical helmet.
2. Microbial sampling was performed on five locations on the left side of the surgical clothing system by using contact plates. The sampling was performed on both the test person and the dummy, see Figure 6.18.
3. The test person and the dummy were exposed in the lunch restaurant at Chalmers University of Technology for 2 hours.
4. After the exposure the microbial sampling was repeated on the five locations on the surgical clothing system but on the right side. The sampling was performed on both the test person and the dummy.

The test was repeated three days a row. The five locations on the surgical clothing system were shoulder, breast, upper arm, thigh and shin, see Figure 6.19.

Figure 6.18 Microbial surface sampling performed on the surgical clothing system of the test dummy (Photo B. Reinmüller in Jordestedt (2015)).

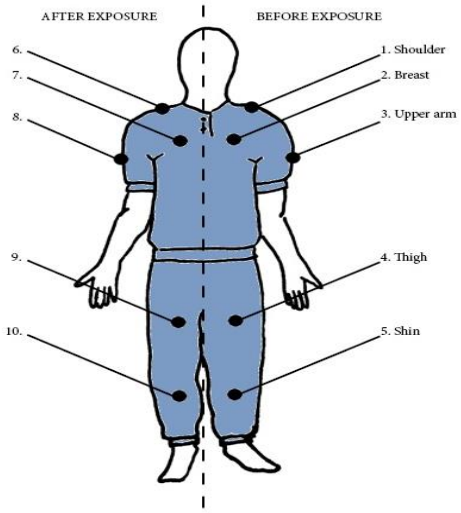


Figure 6.19 Chosen sampling locations on the surgical clothing system before and after exposure (Jordestedt (2015)).

Observational study in an orthopedic surgical department

The measurement study at the orthopedic surgical department was performed during a five-day period and each day included test on surgical clothing systems worn by 3 persons with exception of the last day that included 1 person. Samplings were performed on 13 sets of the clothing systems. Four locations - shoulder, breast, thigh and shin - for microbial sampling were chosen on the surgical clothing system, see Figure 6.20.

Figure 6.20 Sampling sites on the surgical clothing system.

The performance of the measurement study at the orthopedic surgical department was as following:

1. At the beginning of the working day
   After the test persons had changed from private clothing to the surgical clothing system, the microbial sampling was performed on the four locations on the surgical clothing system.
   Due to contamination of the outside of the clothing with agar, the personnel changed to a new set of surgical clothing after the performed sampling.

2. At the end of the working day
   The microbial sampling was repeated on the four locations on the surgical clothing system. During the working day, the surgical clothing system had been exposed in different environments. Each test person reported their movements within the surgical department during their working day, and if they had visited uncontrolled areas outside the surgical department.

6.3 Evaluation of Clothing System - Source Strength during Ongoing Surgery

Background

The number of airborne bacteria-carrying particles in the operating room is considered as an indicator of the risk of infection to the patient undergoing surgery susceptible to infections. It is important to keep the bacteria-carrying particles at a low number in the operating room air, especially during orthopedic prosthetic surgery. To reduce the bacteria-carrying particles emitted from the surgical staff in the operating room, the staff wears a clothing system suitable for ultraclean air environment. Surgical clothing systems work as filters and their protective efficacy (source strength)is described as the mean value of the number of total or airborne bacteria-carrying particles per second emitted from one person.

Several studies have been performed to investigate and determine the protective efficacy of different surgical clothing systems both in dispersal chambers and during ongoing surgery in operating rooms (Reinmüller and Ljungqvist (2000, 2003), Ljungqvist and Reinmüller (2004, 2014), Kasina et al (2016), Romano et al (2016), Tammelin et al (2012, 2013), Whyte and Hejab (2007)) and Ullmann et al (2017b)).

Purpose

The purpose of the airborne microbial measurements performed in operating rooms during ongoing orthopedic surgery was to determine the value of the source strength of different types of surgical clothing systems and to evaluate whether the activity level has an impact of the source strength value.

Material

Microbial sampling equipment

Airborne viable particles were collected using a slit-to-agar sampler, FH3®, and a sieve sampler, MAS-100®, see Figures 6.21 and 6.22. The sampling periods for the two instruments were 10 minutes. The sampling volume per period was for the FH3® sampler 0.5m^3 and for the MAS-100® sampler 1m^3. The two samplers in comparison to the other impaction samplers have been discussed by Ljungqvist and Reinmüller (1998b, 2008) and Romano et al (2015). Both instruments have a d_{50}-value (cut-off size) less than 2µm and were operated according to the manufacturers´ instruction. Thus, the results from the two samplers are comparable.

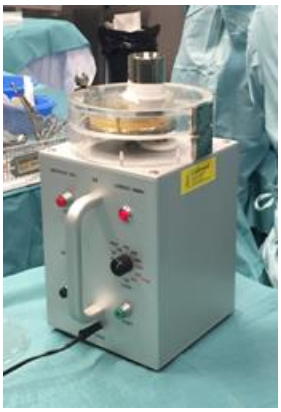


Figure 6.21 Slit-to-agar sampler (FH3®).

Figure 6.22 Sieve sampler (MAS-100®).

Microbial growth medium for all tests was standard medium Tryptic Soy Agar (TSA) in 90mm Petri dishes. The TSA plates were incubated for not less than 72 hours at 32˚C followed by not less than 48 hours at room temperature. After incubation the number of colony-forming units (CFU) were counted and recorded as aerobic CFU/m^3.

Operating rooms

The measurements of airborne bacteria-carrying particles were performed in operating rooms at a hospital in the Stockholm area. The tests were performed during ongoing orthopedic surgery in operating rooms, where the supply air devices were inclined screens. The air movements could be characterized as dilution mixing, i.e., the dilution principle is applicable during ongoing surgery. The supply air was HEPA-filtered with air volume flows of about 0.6-0.9m^3/s, which give ca 17-20 air changes per hour.

Surgical clothing system

The surgical clothing systems included in the measurement study are the following:

- System of mixed material
- System of synthetic fiber olefin without and with textile knee-length boots

The composition of the fabric and the achievement of the different surgical clothing systems are described in Table 6.7.

Table 6.7 Description of the different surgical clothing systems.

Surgical clothing system	Description
System of mixed material 	69% cotton, 30% polyester, 1% carbon fiber. Weight 150g/m^2 Laundered up to approximate 50 times. The system includes blouse and trousers. Cuffs at arms, neck and wrists. In addition, the test subjects wore disposable nonwoven head covering, sterile face mask, sterile gloves, clean but not sterile cotton socks and clean but not sterile open shoes.
System of synthetic fiber olefin    	98% olefin, 2% carbon fiber Weight 125g/m^2 Laundered approximate 20 times. The system includes textile hood, blouse and trousers. Cuffs at arms, neck and wrists. The hood has cuffs at the face and buttons below the chin. In addition, the test subjects wore sterile face mask, sterile gloves, clean but not sterile cotton socks and 1. Clean but not sterile open shoes. 2.Textile knee-length boots over the shoes (laundered ca 10 times).

During surgical procedures the surgeon and the surgical nurse wore an additional disposable sterile coat over the surgical clothing system. Figure 6.23 shows the surgical team dressed in the Olefin surgical clothing system with knee-length boots.

Figure 6.23 The surgical team dressed in the Olefin surgical clothing system with knee-length boots.

Method

The probe of the air sampler was situated just beside the operating table with a distance of approximately 0.8m to 1.2m to the wound site at two alternative locations depending on the position of the surgical team. The sampling probe was positioned just above the operating table 1.2m above the floor. Figure 6.24 shows the principle arrangements of the location of the sampling probe.

During ongoing surgery, Ljungqvist et al (2012) show results with a slit-to-agar sampler (FH3®) placed as in Figure 6.24 with concentration values (CFU/m^3) in the same range as when the probe of a filter sampler (Sartorius MD8®) was situated 30-50cm from the wound site.

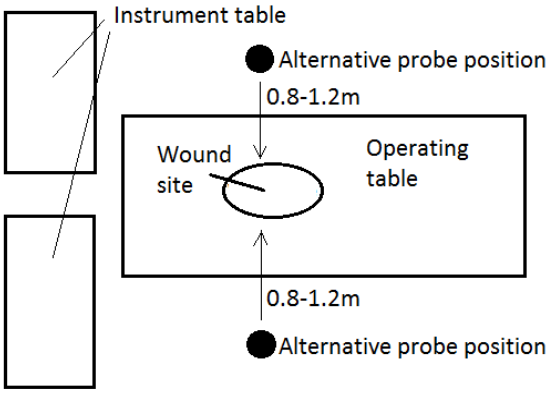


Figure 6.24 Principal arrangement of the alternative placement of the sampling probes beside the operating table.

During the ongoing surgery, present staff was 5-8 persons, and all wore clothes made from the same material during each surgical procedure.

Measurements of airborne viable particles were performed on a regular basis during the complete time for the ongoing surgery.

Figure 6.25 is showing the microbial air sampler (a slit-to-agar sampler, FH3®) during the measurement in the operating room during ongoing surgery.

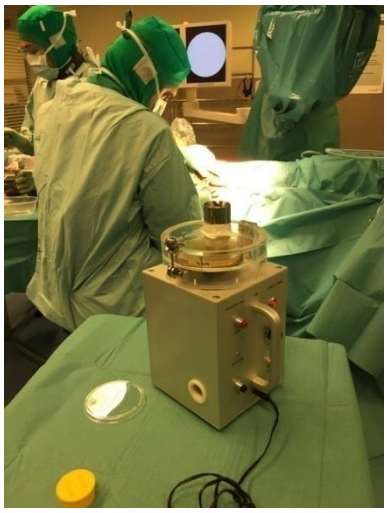


Figure 6.25 The microbial air sampler (slit-to-agar sampler, FH3®) during measurement in the operating room.

6.4 Measurement in Tissue and Cells Establishments

Background

To create a unified framework for the procedure of handling human tissue and cells within the European Union, the Tissue and Cells Directives (EUTCD) were implemented 2007.The directives cover safety and quality for the procedure of handling human tissue and cells within the European Union to secure the human health related to the application of cells and tissues to the human body. Examples of human tissue and cells used for patient treatments are stem cells, bone tissue, corneas, derma, heart valves, cellular therapies and germ cells.

The premises for tissue and cells establishments may vary depending on type of tissue and cells the establishment is handling. Some part of the procedure for bone tissues is performed in operating rooms for orthopedic surgery. Bone tissues are importantly used within orthopedic surgery for repairing deficiencies in bones caused by discharges during hip- and knee implantations.

The Tissue and Cells Directives include requirements for premises and the cleanliness level for airborne particles, airborne bacteria-carrying particles and microorganisms on surfaces. The directives refer to the European Guide to Good Manufacturing Practice (EU GMP)and the operating room shall fulfill grade A where the processing of bone tissue is taken place and having a background environment fulfilling at least grade D.

Purpose

The purpose was to perform measurements in operating room classified as tissue and cells establishment for bone tissue in order to investigate if the premises fulfill the new requirements according to the Tissue and Cells Directives (EUTCD).

Material

Premises

The measurement study was performed at 5 tissue and cells establishments in different hospitals in Stockholm. All the tissue and cells establishments were in orthopedic surgery departments, i.e., in operating rooms, and were handling bone tissues during ongoing surgery. A total of 13 operating rooms were included in the study. Number of operating rooms per tissue and cells establishment, see Table 6.8.

Table 6.8 Summary of number of operating rooms per tissue and cells establishment.

Tissue and cells establishment at hospital	Number of operating rooms within the orthopedic surgery department used for handling tissue and cells
A	1 operating rooms
B	5 operating rooms
C	1 operating room
D	3 operating rooms
E	2 operating rooms

The layouts of the operating rooms can be divided in three main types.

Layout 1:
The entrance to the operating room is directly from a corridor with high activity (transportation of staff, patients and material and equipment for the surgical department), see layout in Figure 6.26. The layout is applicable for hospital A.

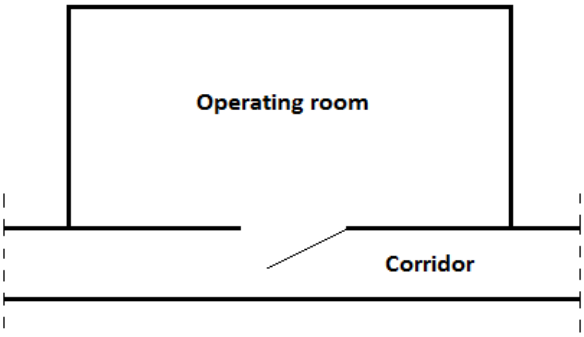


Figure 6.26 Schematic drawing of layout 1.

Layout 2:
The staff entrance into the operating room is directly from a corridor with high activity (transportation of staff, patients and material/equipment for the surgical department) and the intake of the patient into the operating room is through an adjacent preparation room, see layout in Figure 6.27. The layout is applicable for hospital B and E.

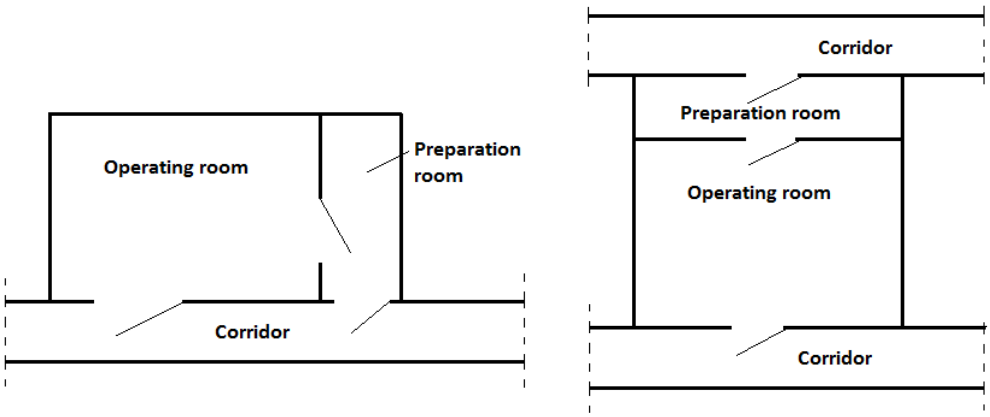


Figure 6.27 Schematic drawings of layout 2.

Layout 3:
Adjacent to the operating room is a washing room (entrance for the staff) and a preparation room for intake of the patient to the operating room, see layout in Figure 6.28. The layout is applicable for hospital C and D.

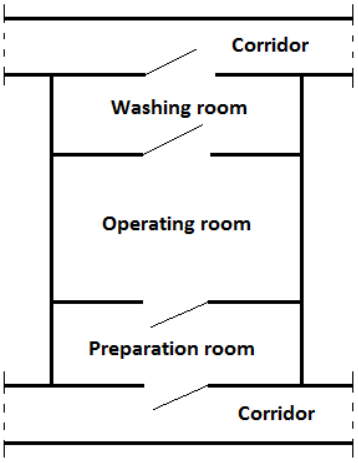


Figure 6.28 Schematic drawing of layout 3.

Ventilation

The air movements in 7 of the operating rooms could be characterized as dilution mixing, i.e., dilution principle is applicable during ongoing surgery. The other 5 operating rooms were equipped with unidirectional airflow (mainly vertical) at the zone where the surgical procedure was performed.

Type of ventilation principle in the different operating rooms for each hospital including the air volume flow and air changes per hour, see Table 6.9.

Table 6.9 Summary of the number of operating rooms per tissue and cells establishment, and type of room air distribution system (including air volume flow/air changes per hour) in the rooms.

Tissue and cell establishment at hospital	Type of room air distribution system	Air volume flow, Air changes per hour
A	1 room with vertical unidirectional airflow, approx. 0.32m/s (mean value).	2.6m^3/s, 80 ach
B	1 room with vertical unidirectional airflow, approx. 0.41m/s (mean value).	3.1m^3/s, 131 ach
	4 rooms with dilution mixing air.	0.4-0.55m^3/s, 16-18 ach
C	1 room with vertical unidirectional airflow, approx. 0.26m/s (mean value).	1.6m^3/s, 42 ach
D	1 room with vertical unidirectional airflow, approx. 0.49m/s (mean value).	4.0m^3/s, 120 ach
	2 rooms with dilution mixing air.	0.7m^3/s, 22 ach
E	1 room with horizontal unidirectional airflow, approx. 0.40m/s (mean value).	4.3m^3/s, 109 ach
	1 room with dilution mixing air.	0.7m^3/s, 20 ach

Figure 6.29 shows a picture of one of the operating rooms with dilution mixing air, and Figures 6.30 and 6.31 show operating rooms with a vertical unidirectional airflow unit and a horizontal unidirectional airflow unit, respectively.

Figure 6.29 Operating room with dilution mixing air.

Figure 6.30 Operating room with vertical unidirectional airflow.

Figure 6.31 Operating room with horizontal unidirectional airflow.

Surgical clothing system

The surgical clothing system used for the tissue and cells establishments for bone tissue was essentially a system of mixed material. One of the establishments (hospital D) used a clothing system of a disposable non-woven material. Description of the two surgical clothing systems, see Table 6.10.

Table 6.10 Description of the different surgical clothing systems.

Hospital	Surgical clothing system	Description
A, B, C, E	System of mixed material 	The fabric is 69% cotton, 30% polyester, 1% carbon fiber and the weight 150g/m^2. The system includes blouse and trousers. Cuffs at arms, neck and wrists. In addition, the test subjects wore disposable head covering, sterile face mask, sterile gloves, clean but not sterile cotton socks and clean but not sterile open shoes.
D	System of a disposable non-woven material  	The fabric is antistatic treated, and the material is made of spun bonded polypropylene, weight 50g/m^2. The system includes blouse and trousers. Cuffs at arms, waist and wrists. In addition, the test subjects wore disposable head covering, sterile face mask, sterile gloves, clean but not sterile cotton socks and clean but not sterile open shoes.

Methods

The following tests were performed in each operating room (with one exception, see below) used for handling of bone tissues:

- Leakage test of HEPA filters in unidirectional airflow units.
- Visualization of air movements at rest.
- Airflow direction (differential pressure) to adjacent rooms.
- Measurement of airborne particles at rest.
- Measurement of airborne bacteria-carrying particles during ongoing surgery.
- Microbial samplings on different surfaces at the beginning and at the end of the working day.

The operating rooms at hospital E were only available for microbial measurements (airborne bacteria-carrying particles and microorganisms on surfaces).

Leakage test of HEPA filter in unidirectional airflow units

The HEPA filters in unidirectional airflow units were leak tested by using an American Air Techniques TDA-2H aerosol photometer. The leakage test was performed by scanning the filter media and the gasket on the down flow side with the probe of the aerosol photometer during an aerosol concentration of 10-15µg/l in the upstream air. Acceptance criteria was <0.01% leakage.

Visualization of air movements

The predominant air movements within the operating rooms were identified by using smoke. The portable smoke generator, FlowMarker^{TM}, see Figure 6.32,was used for generation of smoke. The smoke broke down into carbon dioxide and water and did not contaminate the room during use.

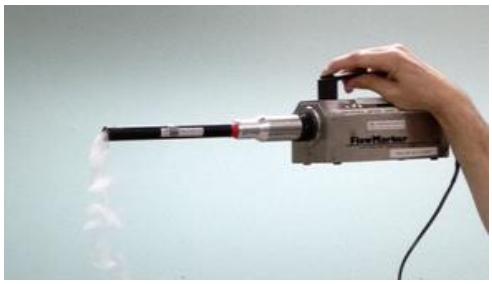


Figure 6.32 The portable smoke generator FlowMarker™.

The visualization was performed during at rest, i.e., no persons were present in the room during the test (with the exception of the two persons performing the test). The temperature of the smoke was in the same range as the room temperature during the visualization.

Airflow direction (differential pressure) to adjacent rooms

A manometer instrument of type TSI9555P was used to measure airflow directions (differential pressure) from the operating room to adjacent rooms.

Measurement of airborne particles

Airborne particles were measured at rest by using a particle counter of type PMS Lasair II. The sampling flow was 1cft/min. Number of sampling points were 2-7 per room (rooms with unidirectional airflow 1 point within the UDF-protected area and 1-2 outside, rooms with dilution mixing air the points were placed evenly in the room). The sampling time was 3-5 minutes at each point and the probe position was approximately 1.2m above floor.

Measurement of airborne bacteria-carrying particles

The measurement of airborne bacteria-carrying particles in the operating room was performed by using active air sampling with a MAS-100® sieve sampler. The sampling flow was 100L/min.

Two locations in the operating room were measured at the same time for the active air sampling; one close to the wound site (position 1) and one in the periphery of the room (position 2), see the principle arrangements of the sampling probe locations in Figure 6.33.

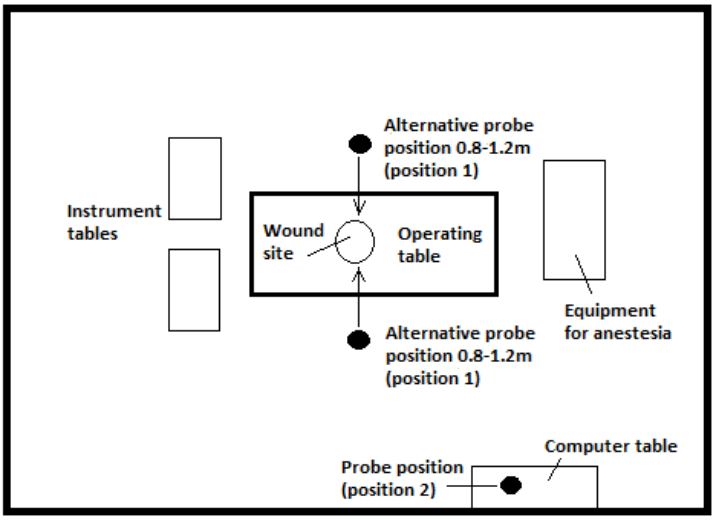


Figure 6.33 The locations of the sampling probe in the operating room.

The sampling probe for position 1 was located just above the operating table, approximately 1.2m above the floor. The probe for position 2 was located on a computer table, approximately 1.2-1.4m above floor.

Microbial growth medium for all tests was standard medium Tryptic Soy Agar (TSA) in 90mm Petri dishes. The TSA plates were incubated for not less than 72 hours at 20-25˚C followed by not less than 48 hours at 30-35˚C. After incubation the number of colony-forming units (CFU) were counted and recorded as aerobic CFU/m^3.

Microbial surface sampling

Microbial surface samplings were performed in the operating rooms in the beginning of the working day (before or during the preparation process). The procedure was repeated in the same locations at the end of the working day, i.e., after the last surgery for the day in the operating room.

A total of 4-6 sampling locations per operating room. Surfaces included in the sampling were:

- *Horizontal surfaces* within the operating room, for example stainless steel tables used for sterile instrument, computer table, commode with consumable goods, see Figure 6.34, and anesthesia equipment, see Figure 6.35.
- *The floor* in the operating room, see Figure 6.36, and outside at the entrance to the operating room.

Figure 6.34
Surface sampling on a commode with consumable goods.

Figure 6.35
Surface sampling on anesthesia equipment.

Figure 6.36
Surface sampling on the floor in the operating room.

Contact plates of type RODAC (Replicate Organism Detection And Counting) were used for the microbial surface sampling. The microbial growth medium was standard medium Tryptic Soy Agar (TSA) in 55mm Petri dishes. The sampling plates were gamma-irradiated and delivered in triple wrapped package. After performed sampling, the TSA contact plates were incubated for not less than 72 hours at 20-25˚C followed by not less than 48 hours at 30-35˚C. After incubation the number of colony-forming units (CFU) were counted and recorded as CFU/plates, i.e., CFU/24cm^2.

7 RESULT - AUTOCLAVES

7.1 Mapping of Air Movements, Air Velocities and Temperatures

Air movements

The temperature difference between the air in the chamber and the ambient air causes flow of air through the openings of the autoclave. The outflow will occur in the upper part of the opening and inflow of air from the room will occur in the lower part. The visualization of air movements and the temperature measurements showed that the inflow of air covers 2/3 of the opening area and the outflow 1/3.

Figures 7.1 and 7.2 show the results for the air movements through the opening of the autoclave with a temperature difference between the air in the chamber and the ambient air. The temperature of the air in the chamber was above the ambient air.

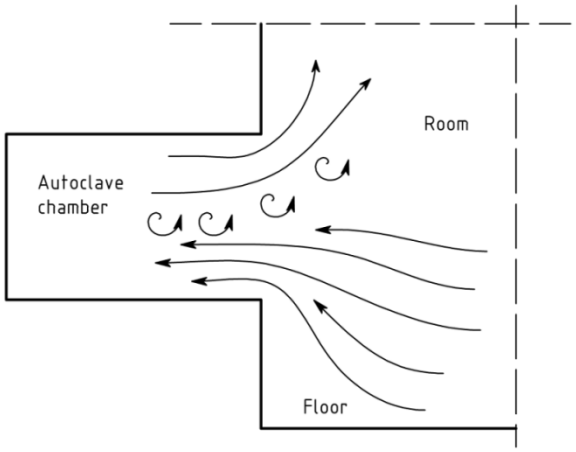


Figure 7.1 Schematically drawing of the air movements through the opening of the autoclave with and without loads in the chamber. The temperature of the air in the chamber is higher than the temperature of the ambient air.

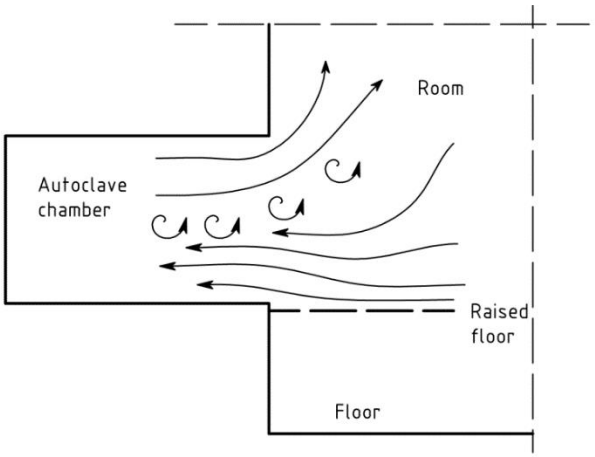
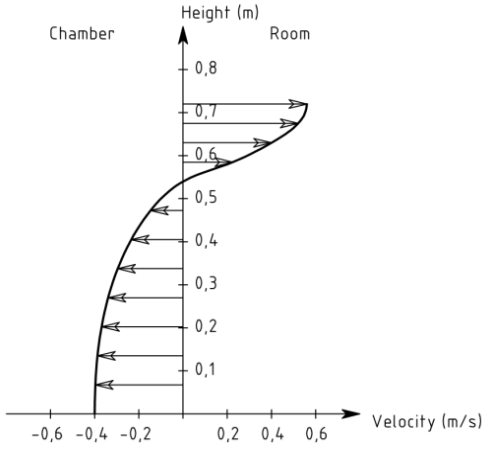


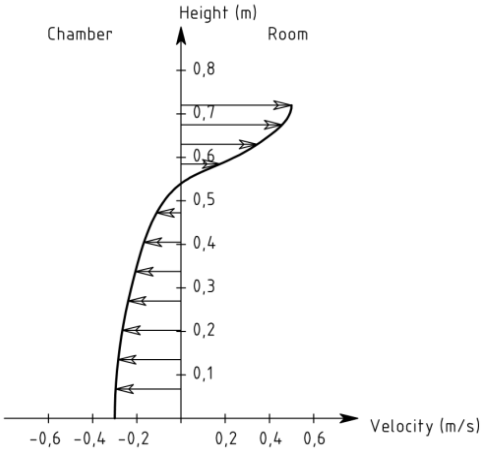
Figure 7.2 Schematically drawing of the air movements through the opening of the autoclave with a simulated floor and with and without loads in the chamber. The temperature of the air in the chamber is above the temperature of the ambient air.

Air velocities

The air velocity measurements are the base for the air velocity profiles of the airflow through the openings of the autoclave. The differences in result of the measured air velocities between the different cases for the autoclave are very small. The schematically represented air velocity profiles for the autoclave, see Figures 7.3 and 7.4, correspond to all the different cases for the autoclave.

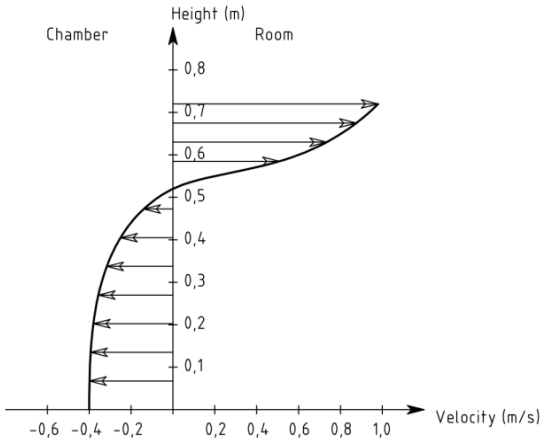


A. At the beginning of the measurement.

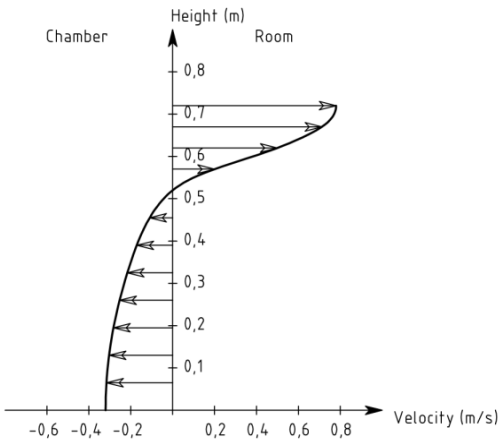


B. After 30 minutes.

Figure 7.3 Air velocity profiles 5cm from the autoclave chamber opening at the beginning of the measurement (A) and after 30 minutes (B).



A. At the beginning of the measurement.



B. After 30 minutes.

Figure 7.4 Air velocity profiles 30-50cm from the autoclave chamber opening at the beginning of the measurement (A) and after 30 minutes (B).

Air temperatures

The results of the temperature measurements give information about the in- and outflow of air through the openings of the autoclave and confirm the results from the visualizations of the air movements; the inflow of air covers 2/3 of the opening area and the outflow 1/3.

Typical test results of the temperature registrations of the in- and outflow air at the autoclave are shown in Figures 7.5 to 7.8.

Figures 7.5 and 7.6 show the comparison in results between the cases without and with load in the chamber. The temperature registration in Figure 7.6 shows that the outflow air has higher temperature values than the air in the chamber. This depends on the temperature probe in the chamber was situated close to the inflowing air. In the cases with loads in the chamber, the temperature of the outflow air was higher at the end of the tests compared to the cases with empty chambers. The loads in the chamber retain the heat. When the door was open after a process run to the autoclave without load in the chamber, the temperature difference between the air in the chamber and the ambient room was around 80°C and decreased to 20°C after 30 minutes. With loaded chamber the temperature difference decreased from 80°C to 50°C after 30 minutes. The result was the same for the cases with raised/simulated floor, see Figures 7.7 and 7.8.

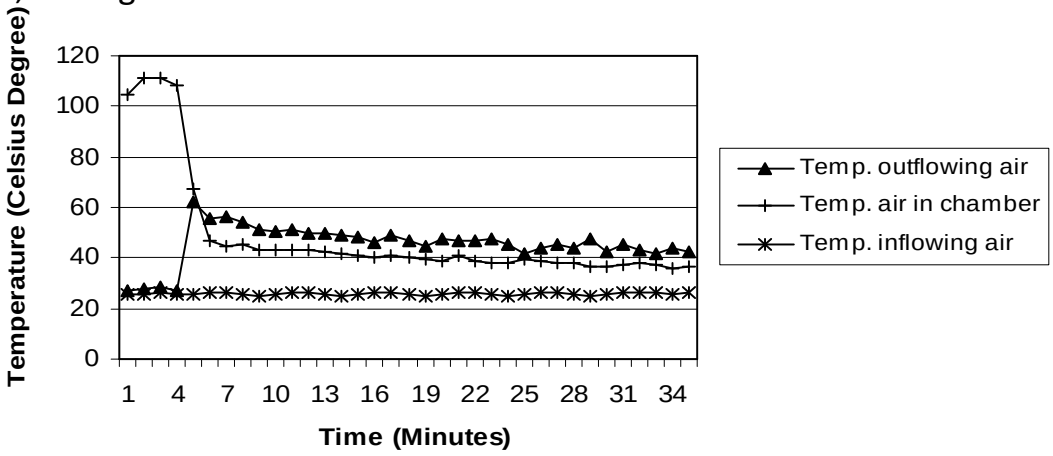


Figure 7.5 Representative temperature registrations of in- and out-flowing air at the autoclave without load in the chamber. The door was opened after 3 minutes.

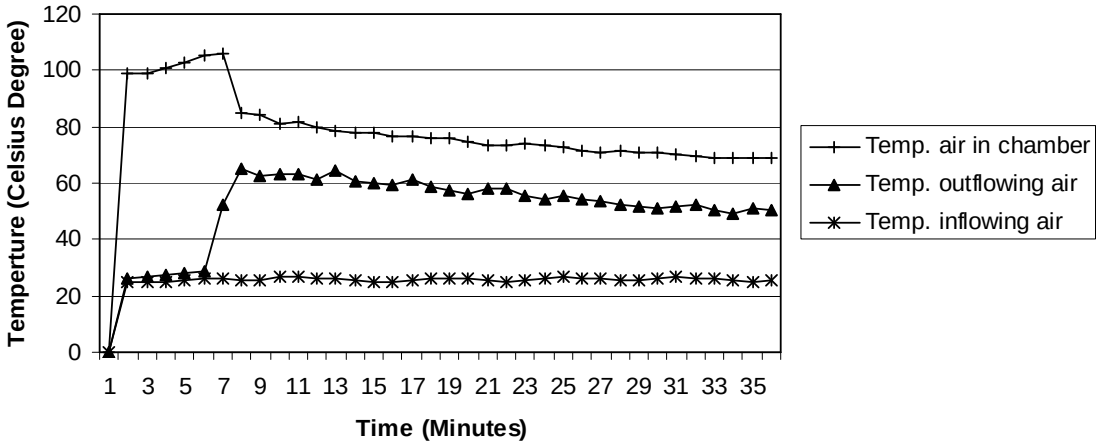


Figure 7.6 Representative temperature registrations of in- and out-flowing air at the autoclave with load in the chamber. The door was opened after 6 minutes.

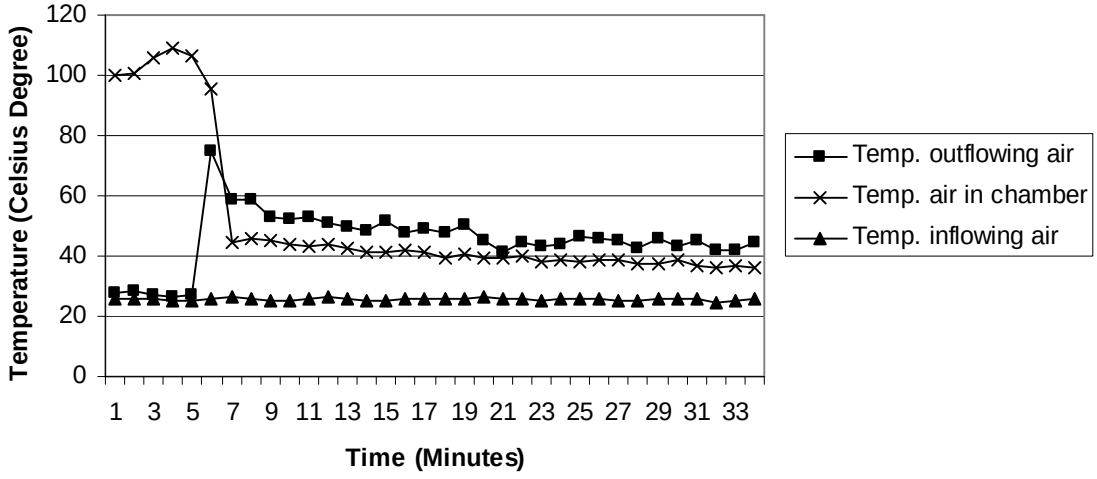


Figure 7.7 Representative temperature registrations of in- and out-flowing air at the autoclave without load in the chamber and with raised floor. The door was opened after 5 minutes.

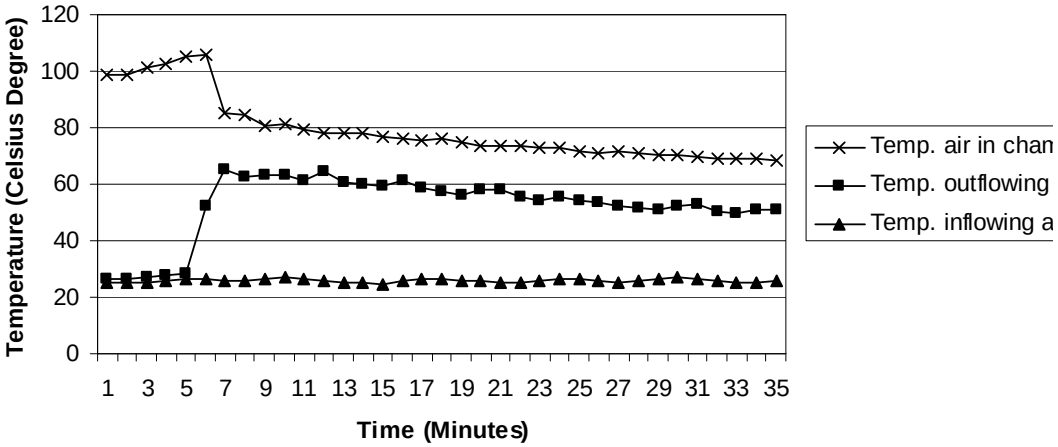


Figure 7.8 Representative temperature registrations of in and out flowing air at the autoclave with load in the chamber and raised floor. The door was opened after 5 minutes.

7.2 Calculation of Discharge Coefficient

To be able to determine the correct discharge coefficient valid for a temperature difference of 20-80°C, the value of the in- and outflow through the opening of the autoclave has to be calculated by using the air velocity profiles and compared to theoretical calculated in- and outflows.

Calculation of discharge coefficient by using air velocity profiles

By using the results from the air velocity profiles, the in- and outflow of air through the opening of the autoclave can be calculated. The in- and outflow can be calculated by:

$$Q_d = v_m \cdot A \qquad (7.1)$$

where v_m = mean air velocity (m/s)
A = area (m^2)

The air velocity profiles give information about the mean air velocity (v_m). The size of the area (A) for the in- and outflow are 2/3 respectively 1/3 of the opening area of the chamber. Table 7.1 present the calculated in- and outflow through the opening of the autoclave based on the results from the measurement studies.

Table 7.1 Calculated in- and outflow through the opening of the autoclave by using the results from the air velocity profiles.

Time	**Distance from the opening** (cm)	**Air Velocity Profile**	**Inflow** (m^3/s)	**Outflow** (m^3/s)
At the beginning of the measurement	5	Figure 7.3 (A)	0.11	0.05
	30-50	Figure 7.4 (A)	0.11	0.08
After 30 minutes	5	Figure 7.3 (B)	0.08	0.04
	30-50	Figure 7.4 (B)	0.08	0.06

Theoretical calculated in- and outflows

By using the equation for calculation of the discharge flow through an opening and the equation for ideal gas, see Part 5.5, the in- and outflow through the opening of the autoclave can be calculated. The calculations are based on two different values of the discharge coefficient; 0.5 and 0.8. The conditions used for the calculation is presented in Table 7.2 and the results of the calculations are presented in Tables 7.3 and 7.4.

Table 7.2 Conditions for the theoretical calculated airflows through the opening of the autoclave.

Factor	**Autoclave**
Discharge coefficient	0.5 and 0.8
Temperature difference:	
- at the beginning of the measurement	81°C
- after 30 minutes	42°C
Size of the opening:	
Width (m)	0.7m
Height (m)	0.7m

Table 7.3 Theoretical calculated in- and outflow through the opening of the autoclave with the discharge coefficient, C_d, 0.5 and 0.8.

Temperature difference (°C)	**In- resp. outflow** (m^3/s)	
	C_d = 0.5	**C_d = 0.8**
81	0.11	0.17
42	0.08	0.13

Comparison of experimentally and theoretically calculated airflows

By comparison of the experimentally calculated airflows, which are based on the experimentally determined air velocity profiles, and the theoretically calculated airflows, it is possible to determine the correct discharge coefficient for the temperature difference of 20-80°C, see Table 7.4. The results show that the experimentally determined values correspond closer to the theoretical values calculated when the discharge coefficient, C_d, was given the value of 0.5.

Table 7.4 Comparison between experimentally and theoretically calculated airflows for the autoclave with the discharge coefficient, C_d, chosen to 0.5 and 0.8.

Case	**Experimentally calculated airflows** (m^3/s)		**Theoretically calculated airflows** (m^3/s)	
	Inflow	**Outflow**	**C_d= 0.5**	**C_d = 0.8**
At the beginning of the measurements	0.11	0.08	0.11	0.17
After 30 minutes	0.08	0.06	0.08	0.13

7.3 Risk Assessment

The first part in the risk assessment - visualization of air movements in case 1 autoclave with no UDF-unit (Table 6.3) - confirmed the result from the study in Part 7.1. The inflow of air into the autoclave chamber occurs in the lower part of the opening and the outflow of chamber air in the upper part. The inflow covers 2/3 of the opening area and the outflow 1/3.

The results from the visualization of the air movements for the cases with a UDF-unit placed on the side of the opening of the autoclave (Cases 2-5, Table 6.3), creating a horizontal airflow in front of the opening, are shown in Figures 7.9 to 7.11.

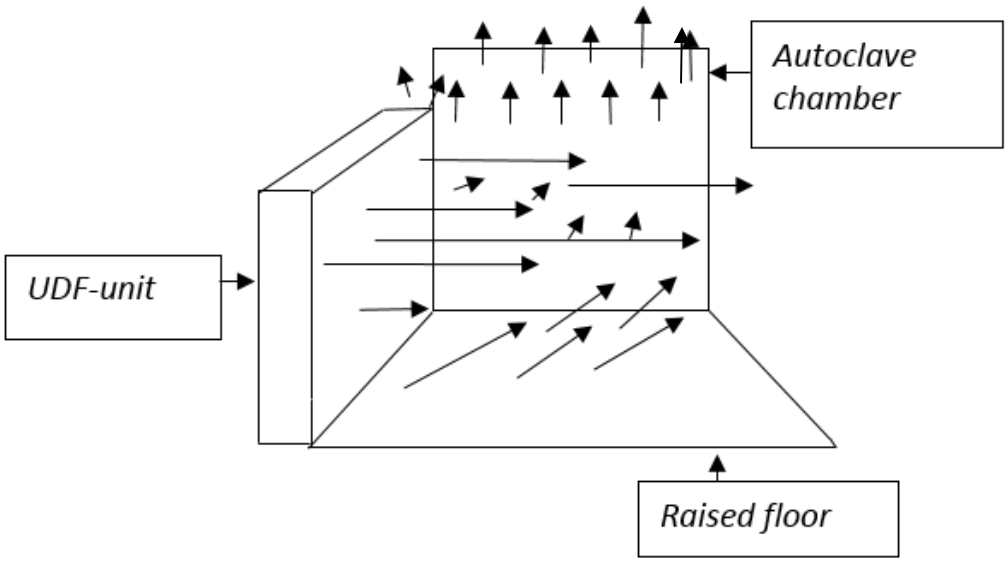


Figure 7.9 Cases 2 and 3: The autoclave provided with a horizontal airflow from a UDF-unit placed on the side of the chamber opening. The air velocity of the horizontal airflow was in average 0.45m/s (Case 2) and 0.65m/s (Case 3).

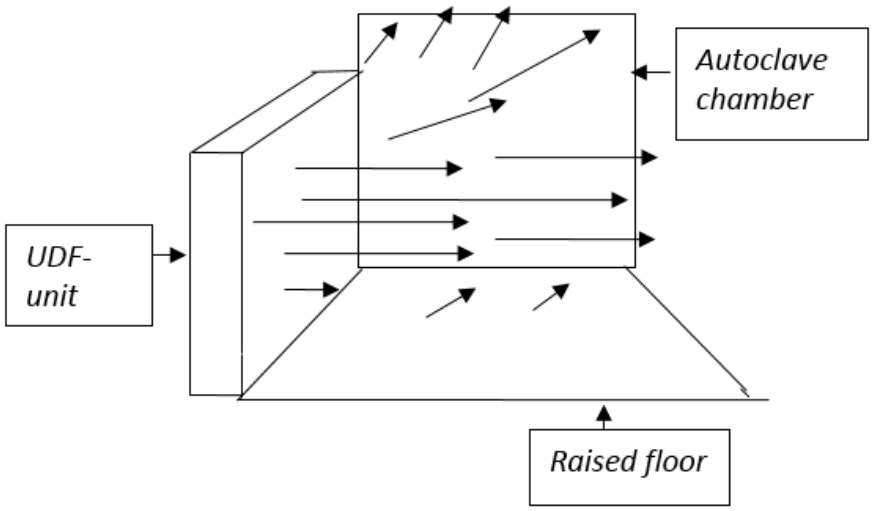


Figure 7.10 Case 4: The autoclave provided with a horizontal airflow from a UDF-unit placed on the side of the chamber opening. The air velocity of the horizontal airflow was in average 1.0m/s.

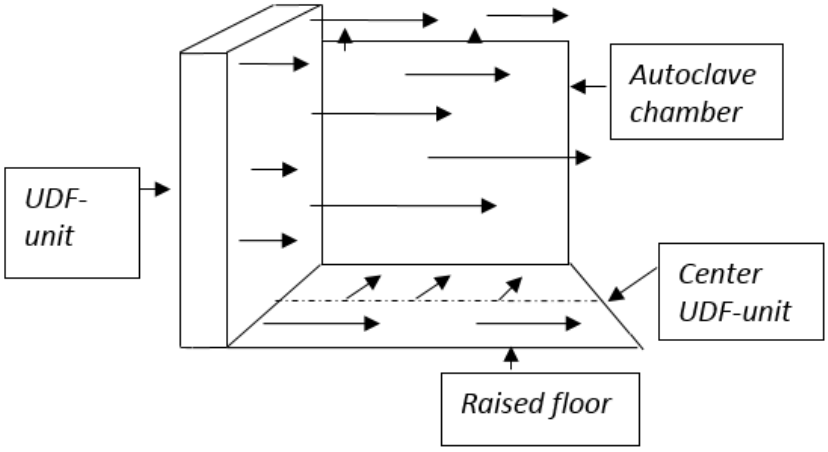


Figure 7.11 Case 5: The autoclave provided with a horizontal airflow from a UDF-unit placed on the side of the chamber opening. The airflow was covering the whole chamber opening and 15cm above the opening. The air velocity of the horizontal airflow was in average 1.0m/s.

Tables 7.5 to7.8 show the results from the challenge test and the calculated risk factors.

Table 7.5 Result of the challenge test and the calculated risk factor. Particles generated in the room (see G1 in Figures 6.6 and 6.7).

Case (Table 6.3)	**Result challenge region G1** (see Table 6.5 and Figures 6.6-6.7)	
	No of particles (≥0.5µm) per ft^3	**Risk factor**
Case 1, without UDF-unit	1 372 959	≥1
Case 2, UDF-unit covering 2/3 of the opening, approx. 0.45m/s	5277	$1.8x10^{-2}$
Case 3, UDF-unit covering 2/3 of the opening, approx. 0.65m/s	102 463	$3.4x10^{-1}$
Case 4, UDF-unit covering 2/3 of the opening, approx. 1.0m/s	47 132	$1.5x10^{-1}$
Case 5, UDF-unit covering the opening, approx. 1.0m/s	60 535	$2.0x10^{-1}$

Table 7.6 Result of the challenge test and the calculated risk factor. Particles generated outside the UDF-unit (see G2 in Figures 6.6 and 6.7).

Case (Table 6.3)	**Result challenge region G2** (see Table 6.5 and Figures 6.6-6.7)	
	No of particles (≥0.5µm) per ft^3	**Risk factor**
Case 1, without UDF-unit	N/A	N/A
Case 2, UDF-unit covering 2/3 of the opening, approx. 0.45m/s	1547	$5.2x10^{-3}$
Case 3, UDF-unit covering 2/3 of the opening, approx. 0.65m/s	10 129	$3.4x10^{-2}$
Case 4, UDF-unit covering 2/3 of the opening, approx. 1.0m/s	3852	$1.3x10^{-2}$
Case 5, UDF-unit covering the opening, approx. 1.0m/s	1543	$5.1x10^{-3}$

Table 7.7 Result of the challenge test and the calculated risk factor (see G3 in Figures 6.6 and 6.7). Particles are emitted only from a person dressed in a coat used for laboratory work.

Case (Table 6.3)	**Result challenge region G3** (see Table 6.5 and Figures 6.6-6.7)	
	No of particles (≥0.5µm) per ft^3	**Risk factor**
Case 1, without UDF-unit	1 270 879	≥1
Case 2, UDF-unit covering 2/3 of the opening, approx. 0.45m/s	746	$2.5x10^{-3}$
Case 3, UDF-unit covering 2/3 of the opening, approx. 0.65m/s	691	$2.3x10^{-3}$
Case 4, UDF-unit covering 2/3 of the opening, approx. 1.0m/s	297	$cax10^{-3}$
Case 5, UDF-unit covering the opening, approx. 1.0m/s	49	$1.6x10^{-4}$

Table 7.8 Result of the challenge test and the calculated risk factor. Particles generated in the UDF-unit area (see G4 in Figures 6.6 and 6.7).

Case (Table 6.3)	**Result challenge region G4** (see Table 6.5 and Figures 6.6-6.7)	
	No of particles (≥0.5µm) per ft^3	**Risk factor**
Case 1, without UDF-unit	N/A	N/A
Case 2, UDF-unit covering 2/3 of the opening, approx. 0.45m/s	1101	$3.67x10^{-3}$
Case 3, UDF-unit covering 2/3 of the opening, approx. 0.65m/s	143 984	$4.8x10^{-1}$
Case 4, UDF-unit covering 2/3 of the opening, approx. 1.0m/s	67 961	$2.3x10^{-1}$
Case 5, UDF-unit covering the opening, approx. 1.0m/s	91 385	$3.0x10^{-1}$

Due to the fact that during the measurements there was a leakage between the UDF-unit and the autoclave side wall, entrainment of room air into the UDF clean air zone occurred. This caused that the Risk factor values became higher than if the values were determined with an air tight construction.

In spite of this, the results in Tables 7.5 to 7.8 show that the contamination risks decrease by using a UDF-unit on the side of the autoclave chamber opening.

7.4 Computer Model

By using the CFD simulation the five different cases presented in Table 6.6 (fictitious autoclave) and Figures 6.9-6.11 were studied. The results comprise of air movements, air velocity profiles and temperature gradient of the air through the opening of the autoclave and when the chamber door has been open in 10 seconds after the process-run.

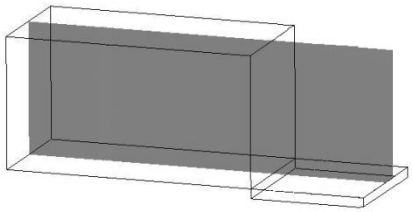
The results of the CFD simulations for the five cases are presented in Figures 7.12-7.38:

- the air movements are shown in Figures 7.12-7.16
- the air velocities are shown in Figures 7.17-7.28
- the air velocity profiles are shown in Figures 7.29-7.33
- the temperature gradients are shown in Figures 7.34-7.38

It should be noted that some of the illustrations of the air movements are shown as three dimensional (3D) figures.

Air movements

The air movements are shown in Figures 7.12-7.16.



Section in the middle of the autoclave chamber, see grey area.

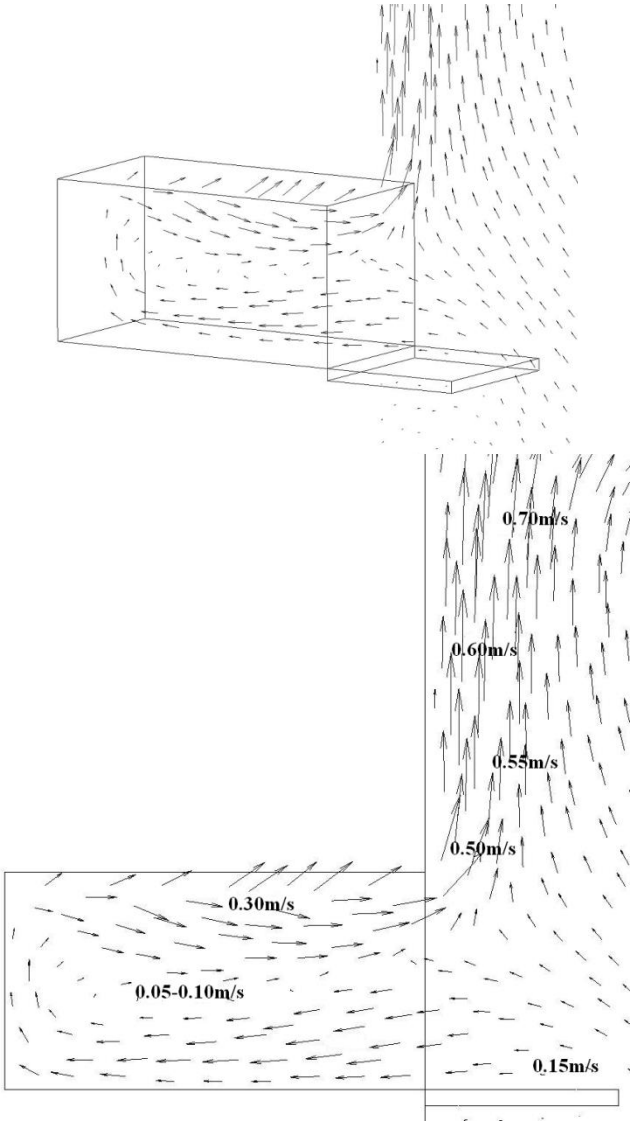
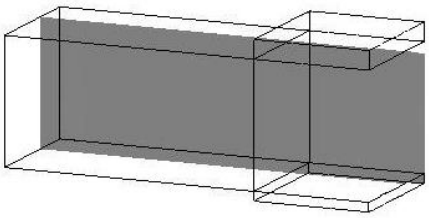


Figure 7.12 Illustration of the air movements (3D) and indication of air velocities in the chamber of the autoclave and in front of the opening in Case 1. No UDF-unit above the opening.



Section in the middle of the autoclave chamber, see grey area.

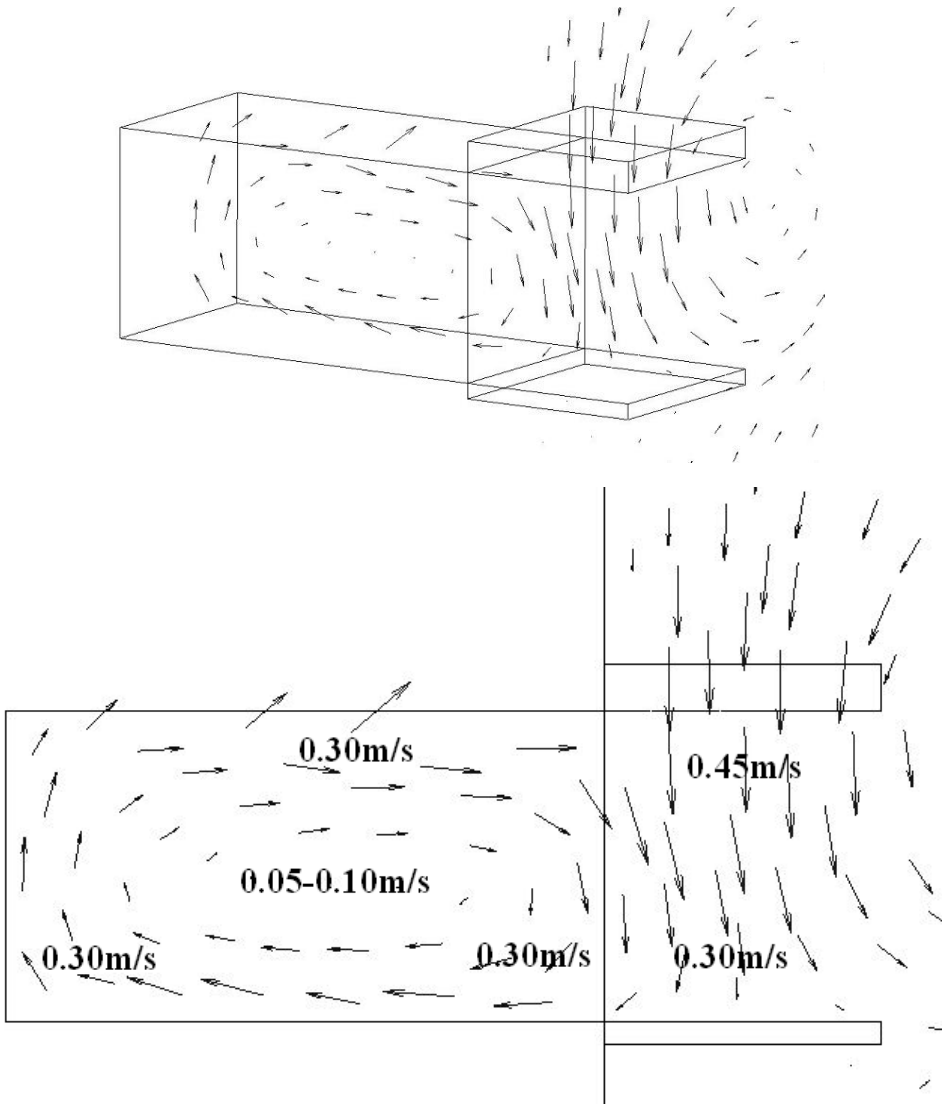
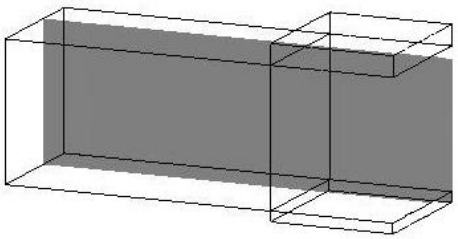
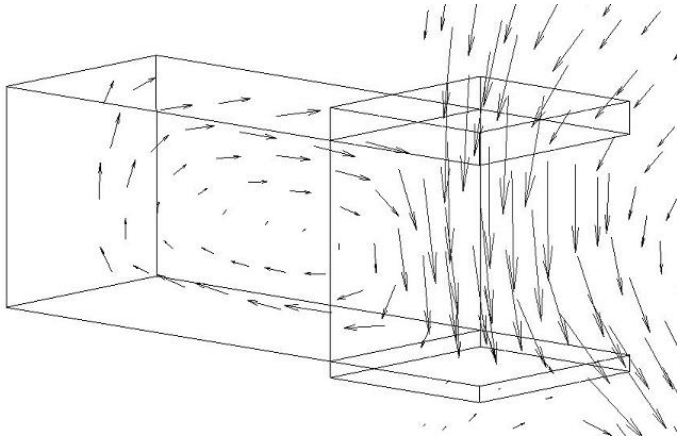


Figure 7.13 Illustration of the air movements (3D) and indication of air velocities in the chamber of the autoclave and in front of the opening in Case 2.The air velocity from the UDF-unit (vertical flow) above the autoclave opening is 0.45m/s.



Section in the middle of the autoclave chamber, see grey area.



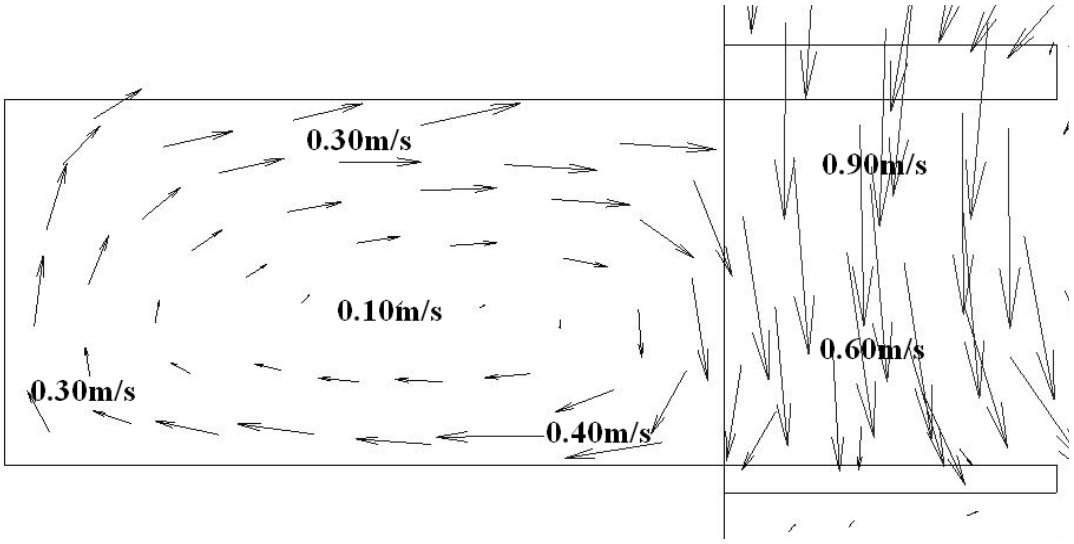


Figure 7.14 Illustration of the air movements (3D) and indication of air velocities in the chamber of the autoclave and in front of the opening in Case 3. The air velocity from the UDF-unit (vertical flow)above the autoclave opening is 0.90m/s.

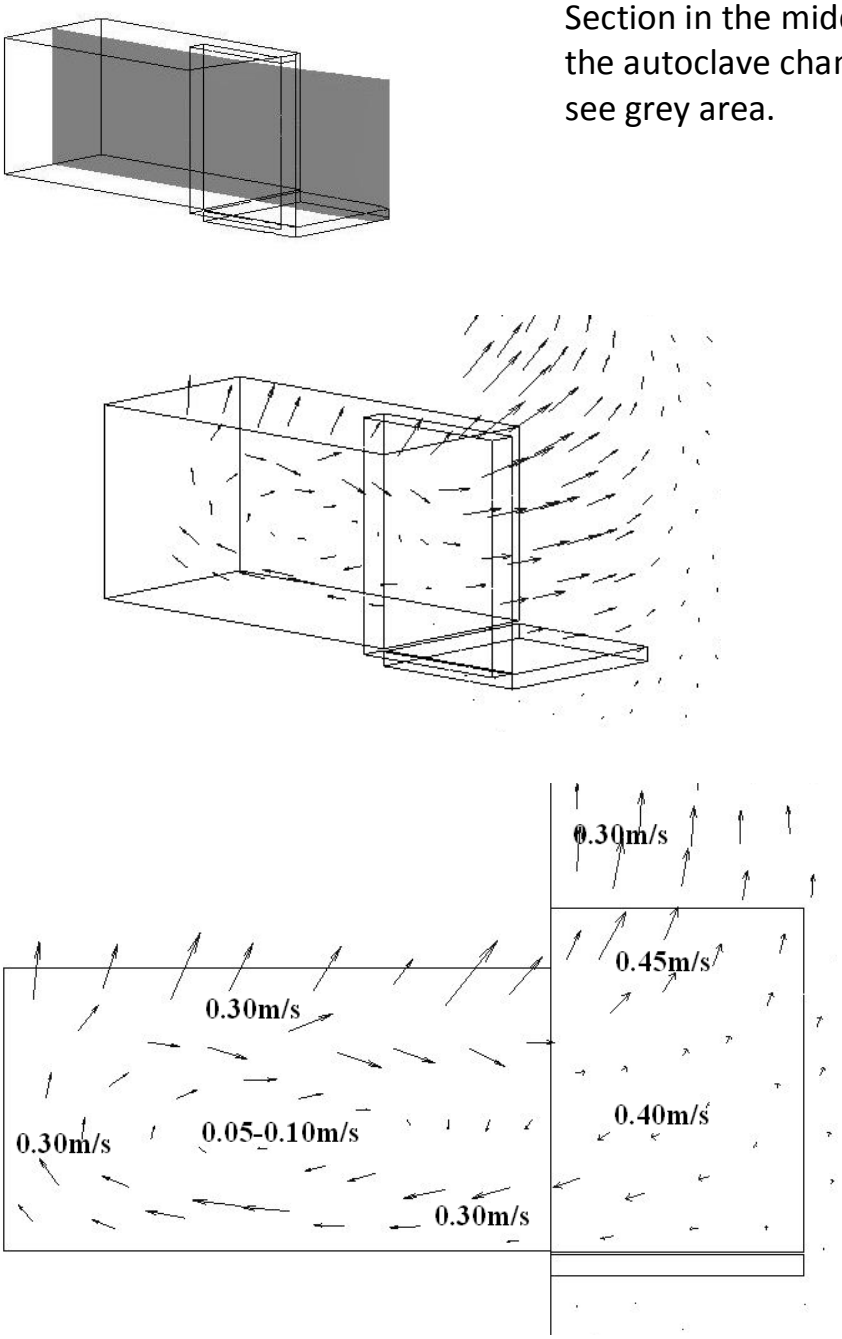
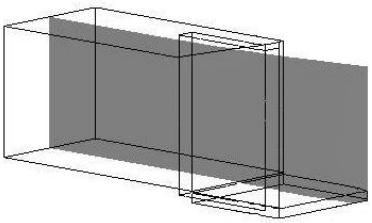
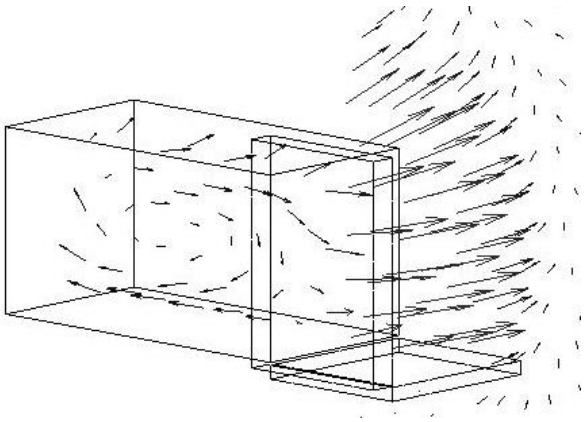


Figure 7.15 Illustration of the air movements (3D) and indication of air velocities in the chamber of the autoclave and in front of the opening in Case 4. The air velocity from the UDF-unit (horizontal flow)on the side of the autoclave opening is 0.45m/s.



Section in the middle of the autoclave chamber, see grey area.



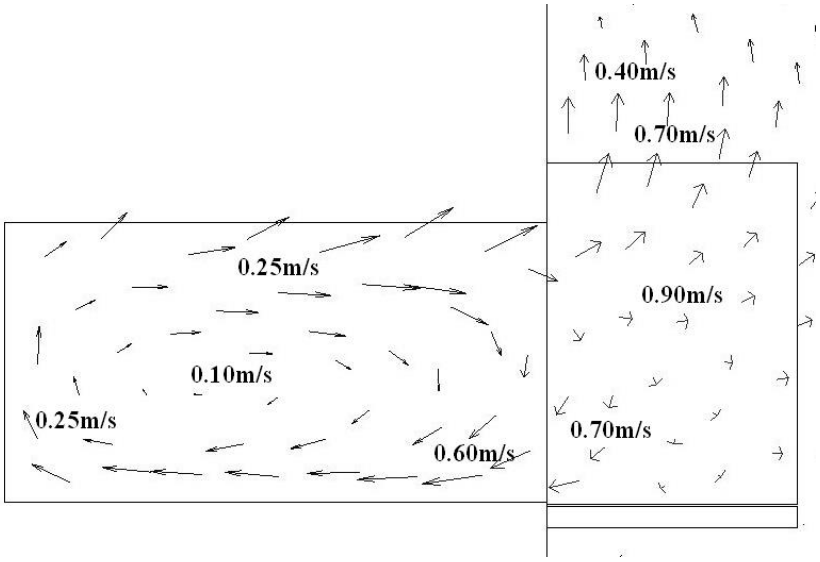
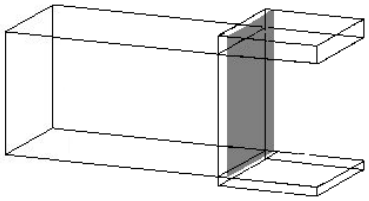


Figure 7.16 Illustration of the air movements (3D) and indication of air velocities in the chamber of the autoclave and in front of the opening in Case 5. The air velocity from the UDF-unit (horizontal flow)on the side of the autoclave opening is 0.90m/s.

Air velocities

Air velocities in Case 2 with the autoclave with a UDF-unit installed above the opening are illustrated in Figures 7.17-7.19. The air velocity of the airflow (vertical flow) from the UDF-unit is 0.45m/s.



Section 5cm from the chamber opening of the autoclave, see grey area.

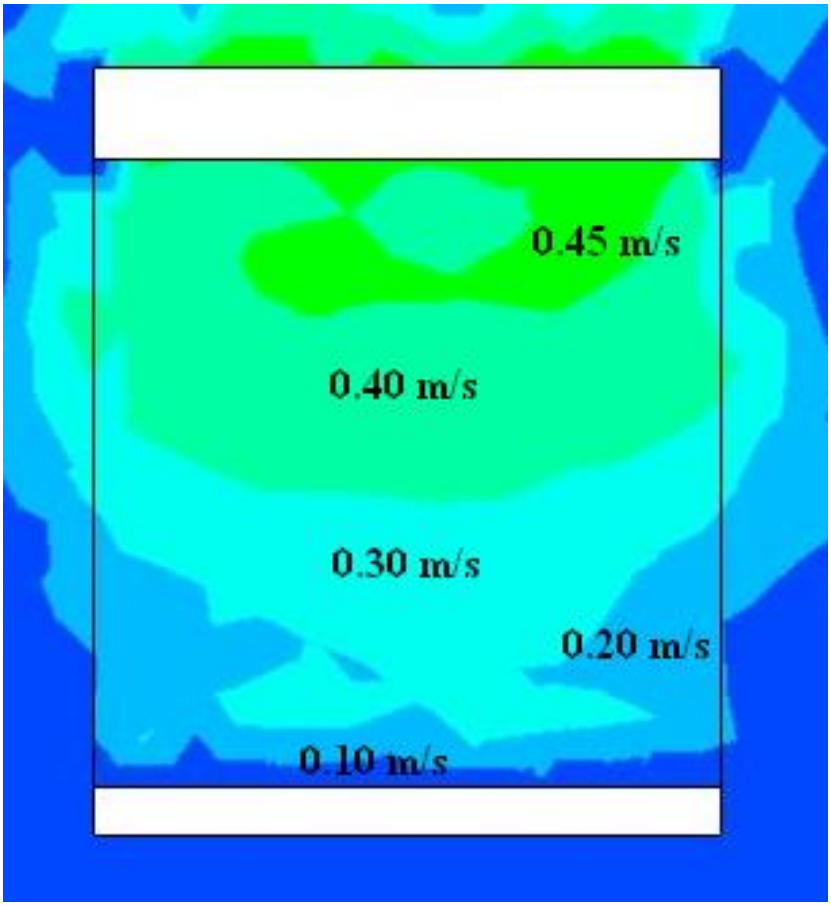
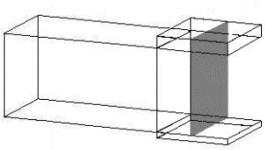


Figure 7.17 Illustration of the air velocity changes from the UDF-unit in Case 2. View from the front and 5cm from the chamber opening.



Section in the middle of the UDF-unit see grey area.

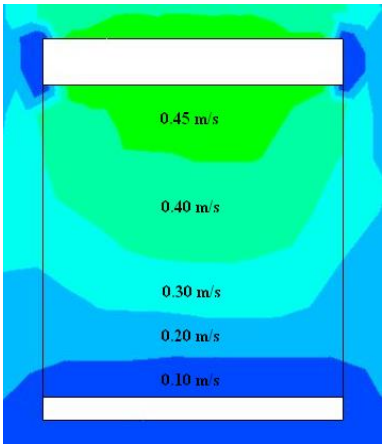
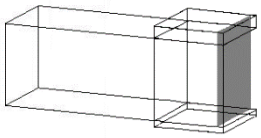


Figure 7.18 Illustration of the air velocity changes from the UDF-unit in Case 2. View from the front and in the middle of the UDF-unit.



Section 55cm from the chamber opening of the autoclave, see grey area.

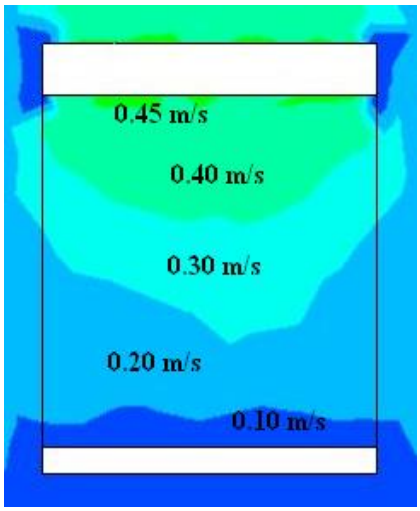
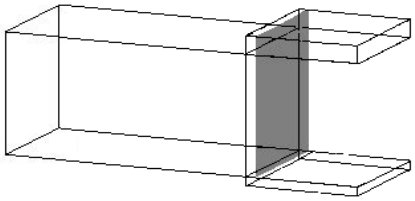


Figure 7.19 Illustration of the air velocity changes from the UDF-unit in Case 2. View from the front and 55cm from the chamber opening.

Air velocities in Case 3 with the autoclave with a UDF-unit installed above the opening are illustrated in Figures 7.20-7.22. The air velocity of the airflow (vertical flow) from the UDF-unit is 0.90m/s.



Section 5cm from the chamber opening, see grey area.

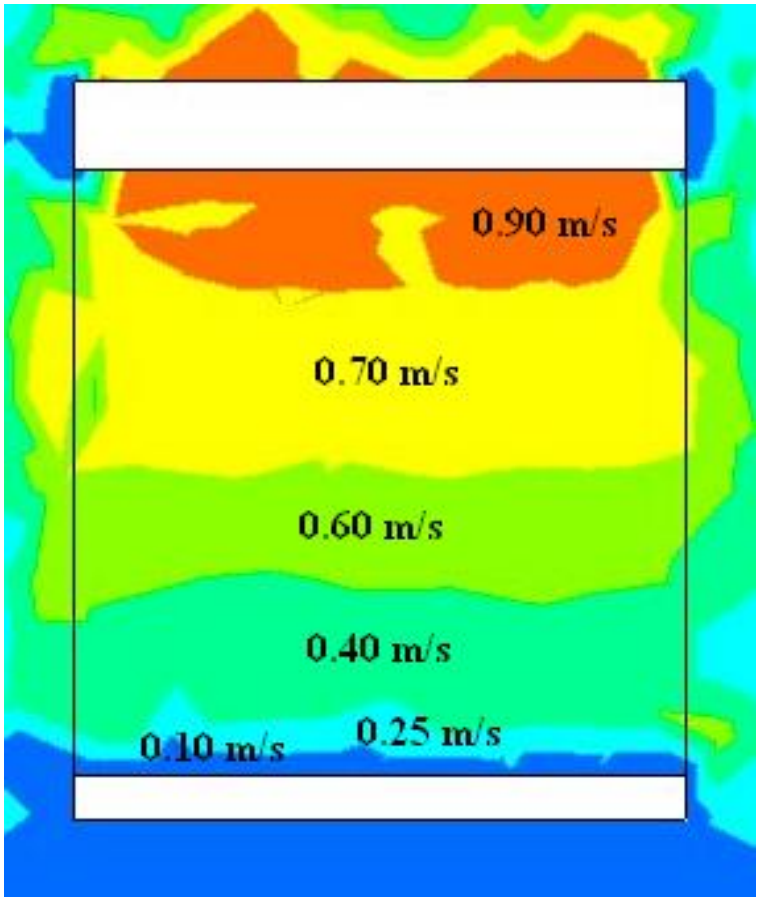
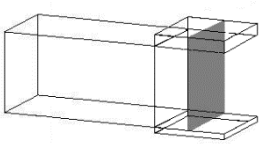


Figure 7.20 Illustration of the air velocity changes from the UDF-unit in Case 3. View from the front and 5cm from the chamber opening.



Section in the middle of the UDF-unit, see grey area.

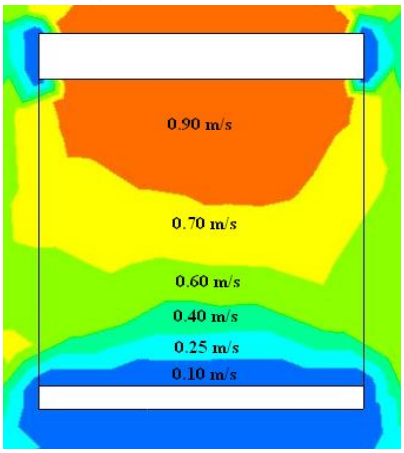
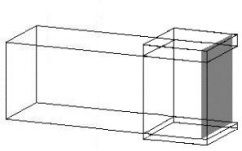


Figure 7.21 Illustration of the air velocity changes from the UDF-unit in Case 3. View from the front and in the middle of the UDF unit.



Section 55cm from the chamber opening of the autoclave, see grey area.

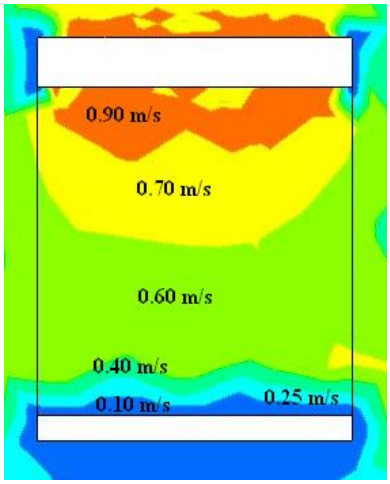
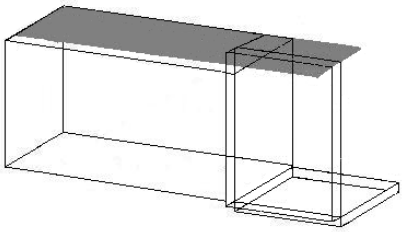


Figure 7.22 Illustration of the air velocity changes from the UDF-unit in Case 3. View from the front and 55cm from the chamber opening.

Air velocities in Case 4 with a UDF-unit installed on the side of the autoclave opening are illustrated in Figures 7.23-7.25. The air velocity of the airflow (horizontal flow) from the UDF-unit is 0.45m/s.



Section 5cm above the opening of the autoclave chamber, see grey area.

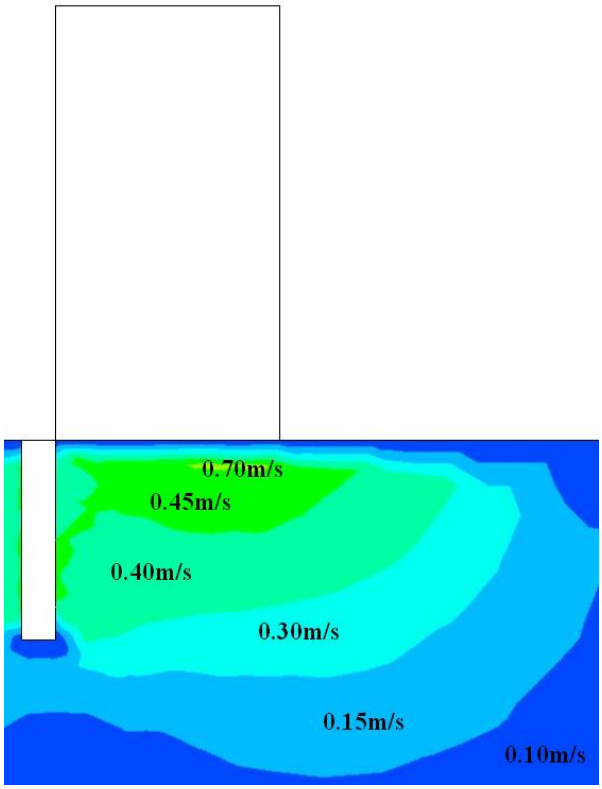
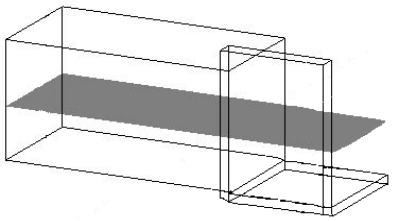


Figure 7.23 Illustration of the air velocity changes from the UDF-unit in Case 4. Top view and 5cm above the chamber opening.



Section in the middle of the autoclave chamber, see grey area.

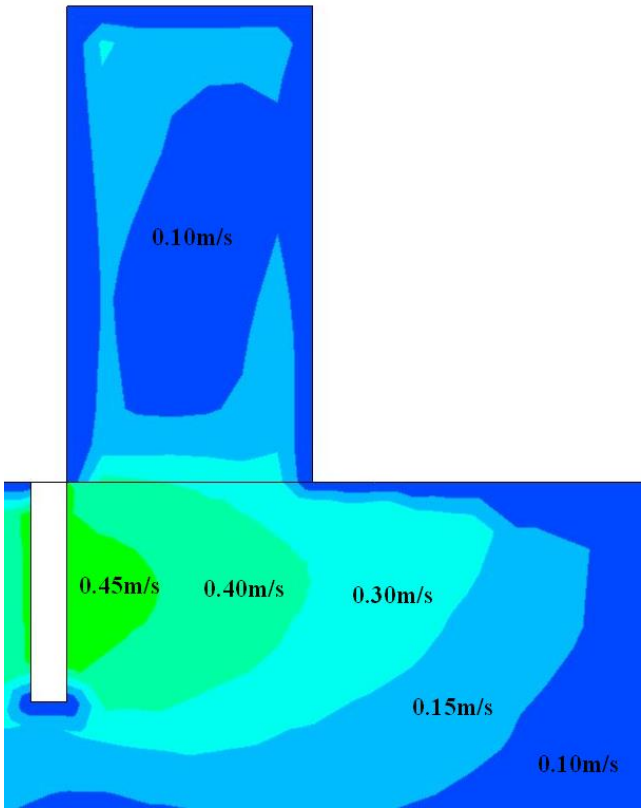
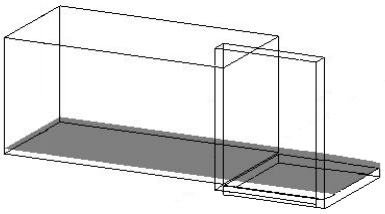


Figure 7.24 Illustration of the air velocity changes from the UDF-unit in Case 4. Top view and in the middle of the UDF-unit and autoclave chamber.



Section 5cm from the bottom of the autoclave chamber, see grey area.

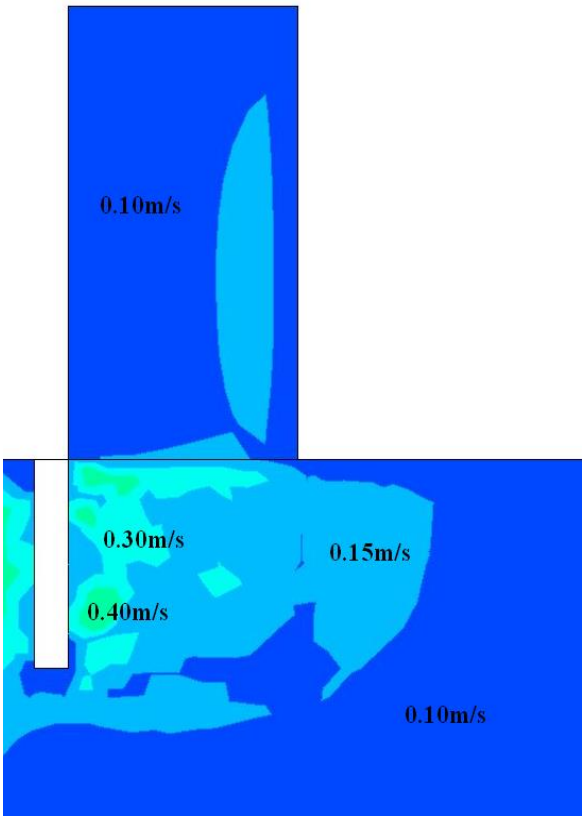
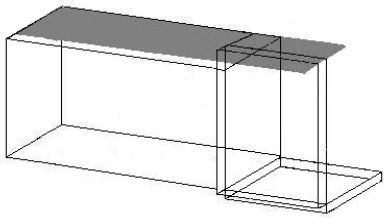


Figure 7.25 Illustration of the air velocity changes from the UDF-unit in Case 4. Top view and 5cm from the bottom of the autoclave chamber.

Air velocities in Case 5 with a UDF-unit installed on the side of the autoclave opening are illustrated in Figures 7.26-7.28. The air velocity of the airflow (horizontal flow) from the UDF-unit is 0.90m/s.



Section 5cm above the opening of the autoclave chamber, see grey area.

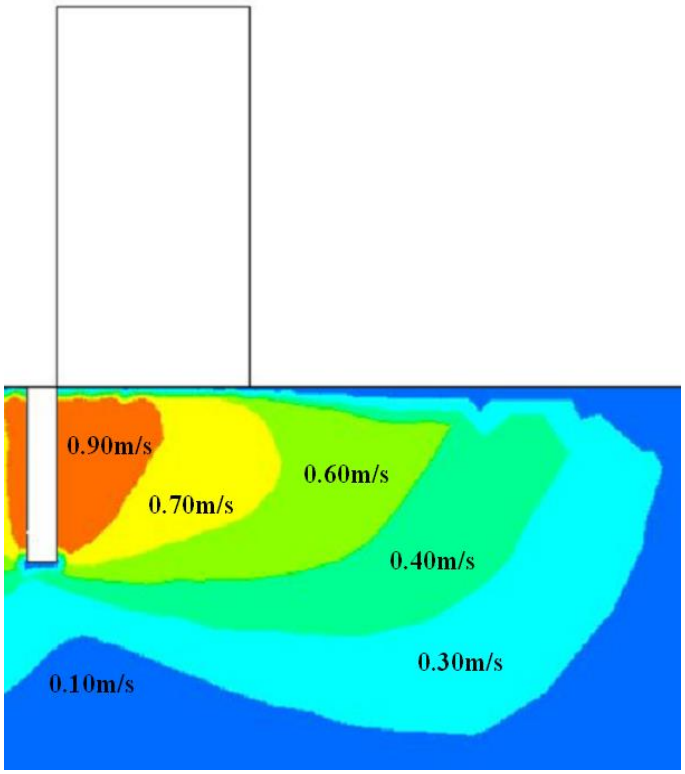
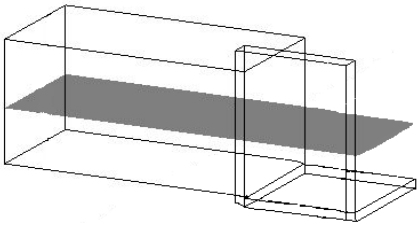


Figure 7.26 Illustration of the air velocity changes from the UDF-unit in Case 5. Top view and 5cm above the opening of the autoclave chamber.



Section in the middle of the autoclave chamber, see grey area.

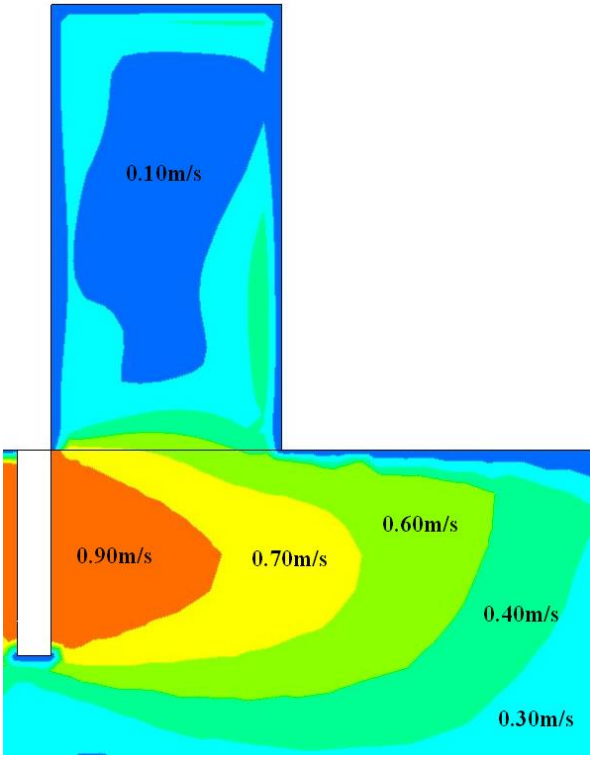
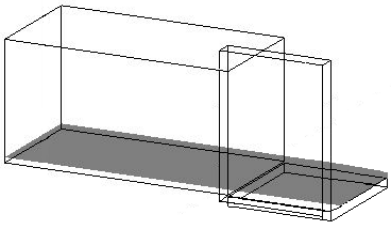


Figure 7.27 Illustration of the air velocity changes from the UDF-unit in Case 5. Top view and in the middle of the UDF-unit and autoclave chamber.



Section 5cm from the bottom of the autoclave chamber, see grey area.

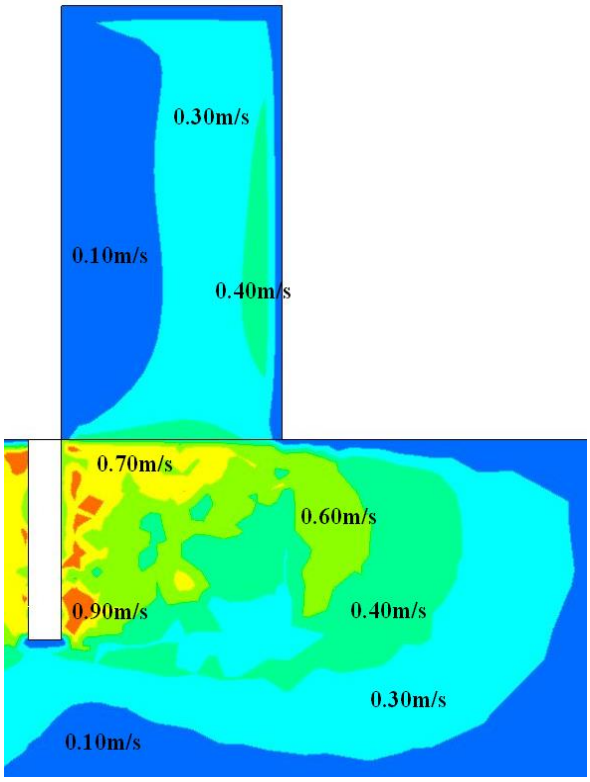


Figure 7.28 Illustration of the air velocity changes from the UDF-unit in Case 5. Top view and 5cm from the bottom of the autoclave chamber.

Air velocity profiles

Velocity profiles for Case 1-5 are shown in Figures 7.29- 7.33.

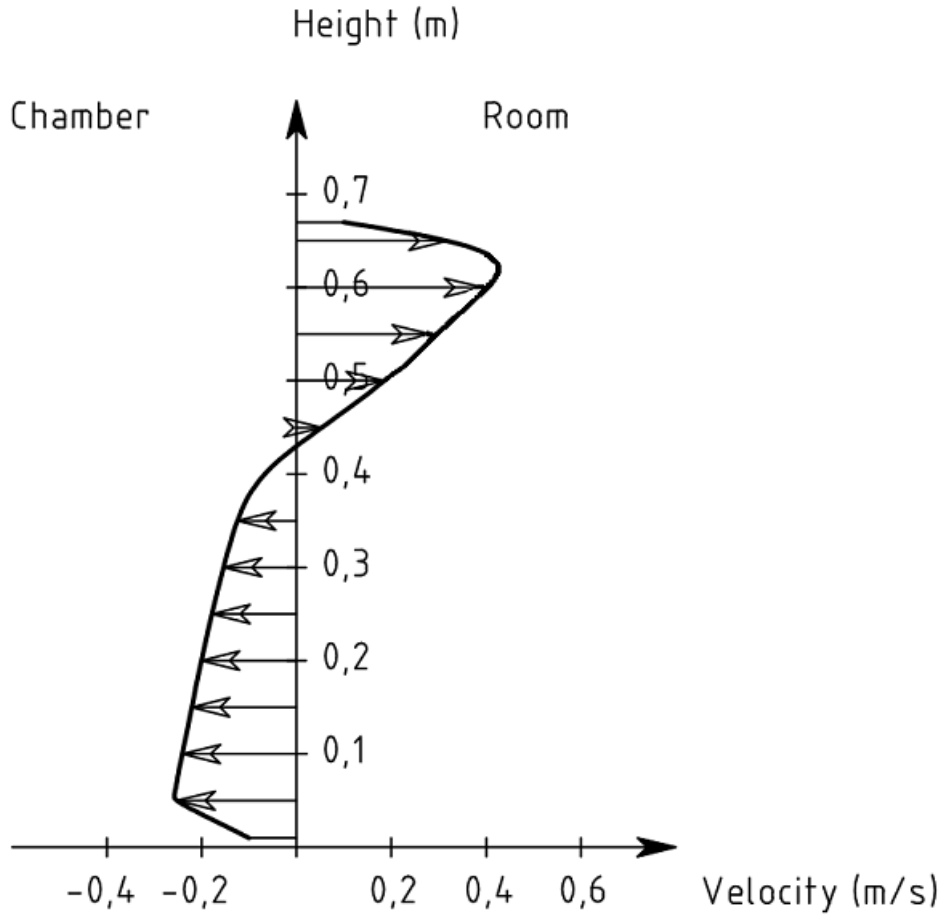


Figure 7.29 Air velocity profile of the air through the chamber opening of the autoclave for Case 1 without UDF-unit.

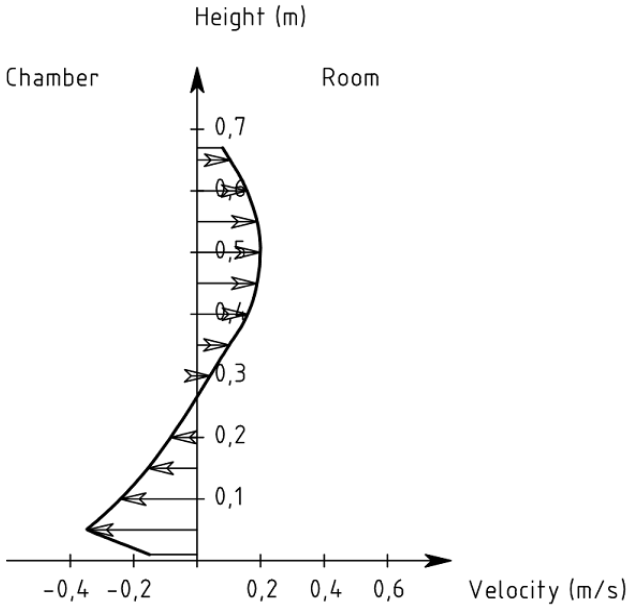


Figure 7.30 Air velocity profile of the air through the chamber opening of the autoclave for Case 2. The air velocity (vertical flow) from the UDF-unit is 0.45m/s.

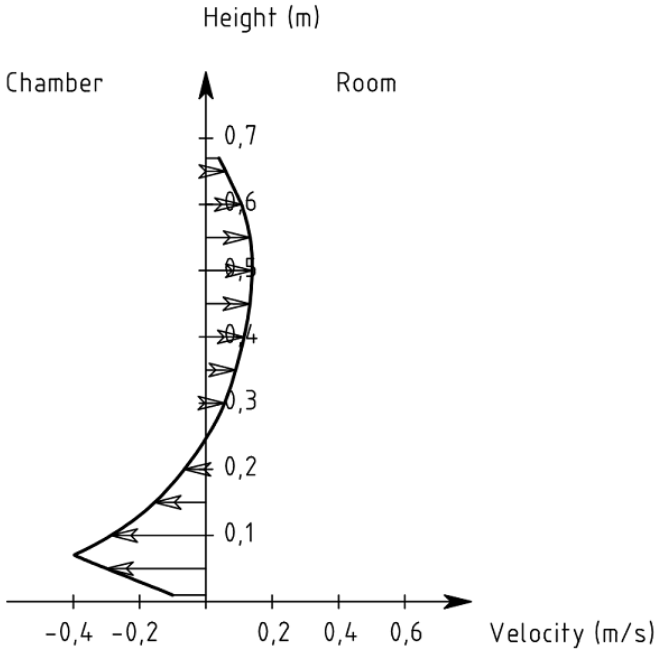


Figure 7.31 Air velocity profile of the air through the chamber opening of the autoclave for Case 3. The air velocity (vertical flow) from the UDF-unit is 0.90m/s.

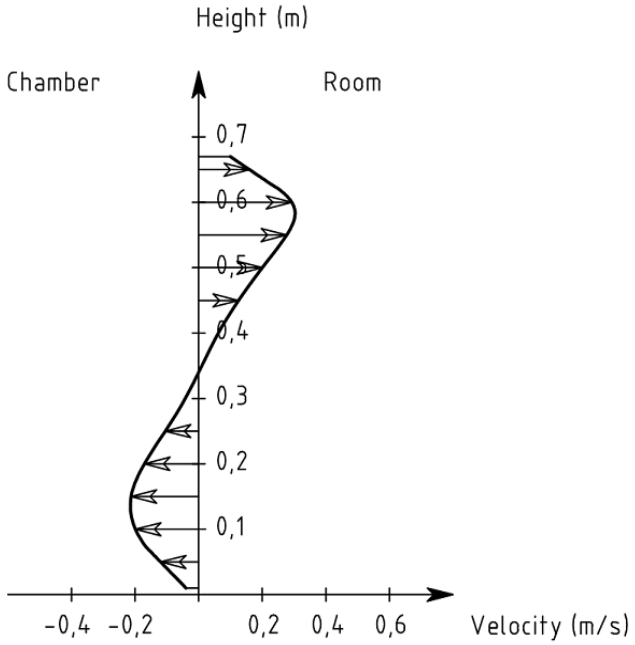


Figure 7.32 Air velocity profile of the air through the chamber opening of the autoclave for Case 4. The air velocity (horizontal flow) from the UDF-unit is 0.45m/s.

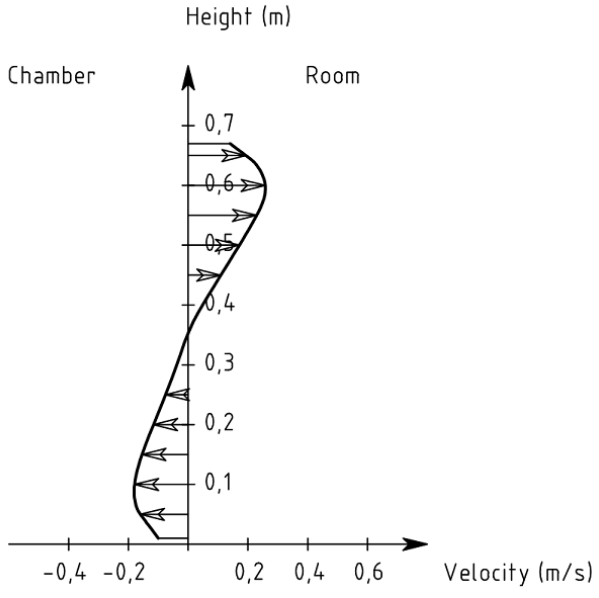
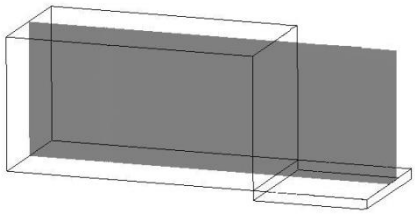


Figure 7.33 Air velocity profile of the air through the chamber opening of the autoclave for Case 5. The air velocity of the airflow (horizontal flow) from the UDF-unit is 0.90m/s.

Temperature gradients

The temperature gradients for Case 1-5 are shown in Figures 7.34-7.38.



Section in the middle of the autoclave chamber, see grey area.

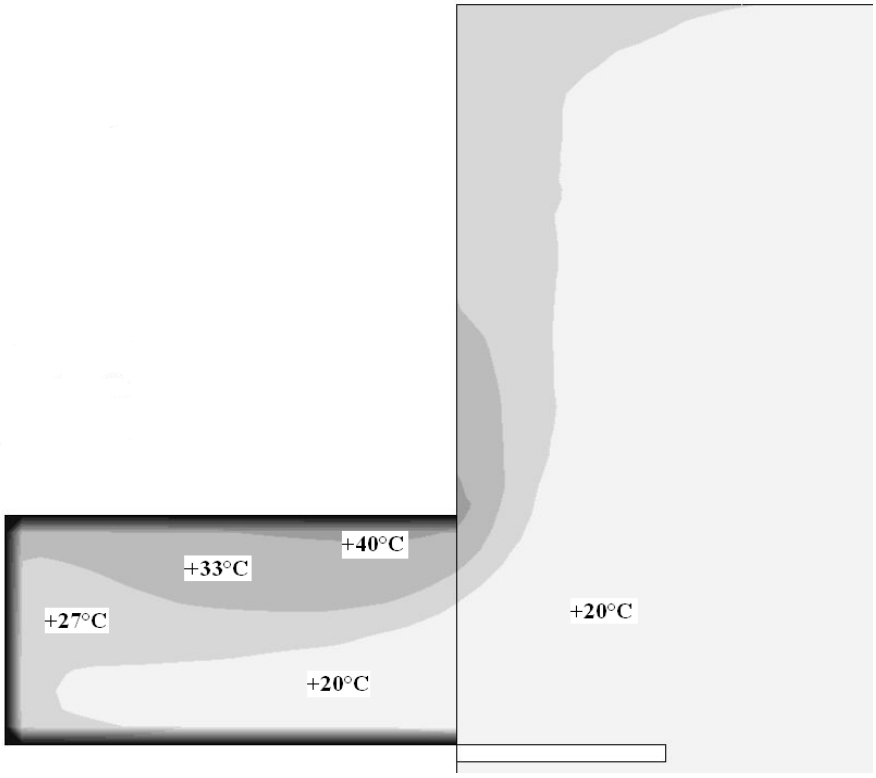


Figure 7.34 Illustration of the temperature gradients of the in- and out-flowing air through the chamber opening of the autoclave in Case 1 without UDF-unit.

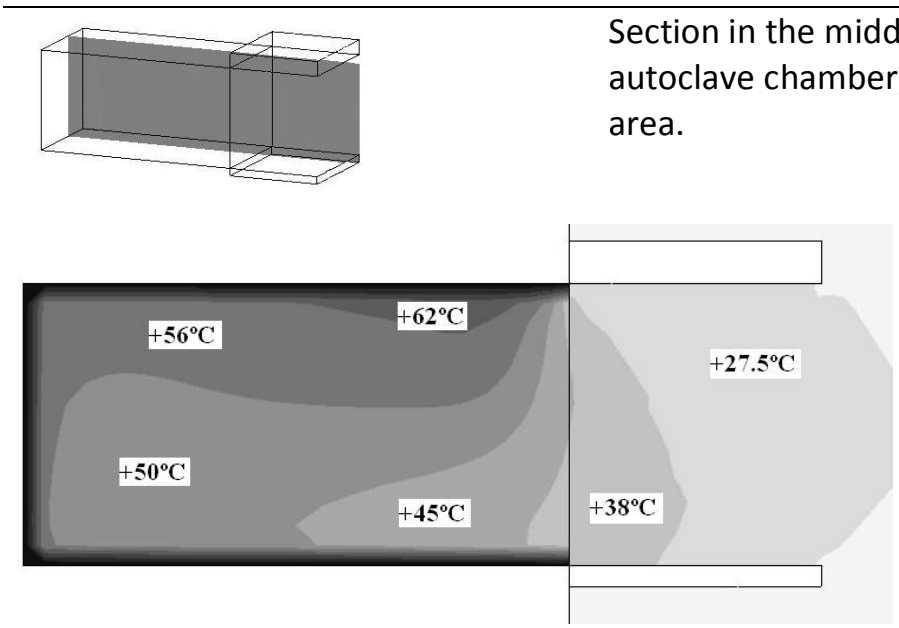


Figure 7.35 Illustration of the temperature gradients of the in- and out-flowing air through the chamber opening of the autoclave in Case 2, UDF-unit above the opening. The air velocity (vertical flow) is 0.45m/s.

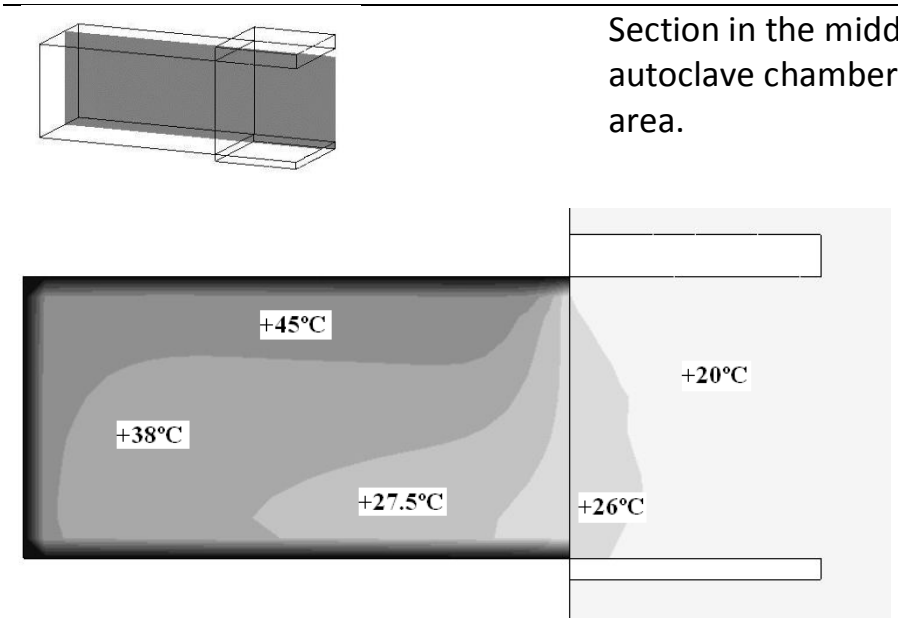
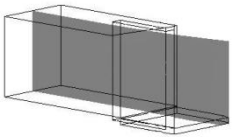


Figure 7.36 Illustration of the temperature gradients of the in- and out-flowing air through the chamber opening of the autoclave in Case 3, UDF-unit above the opening. The air velocity (vertical flow) is 0.90m/s.



Section in the middle of the autoclave chamber, see grey area.

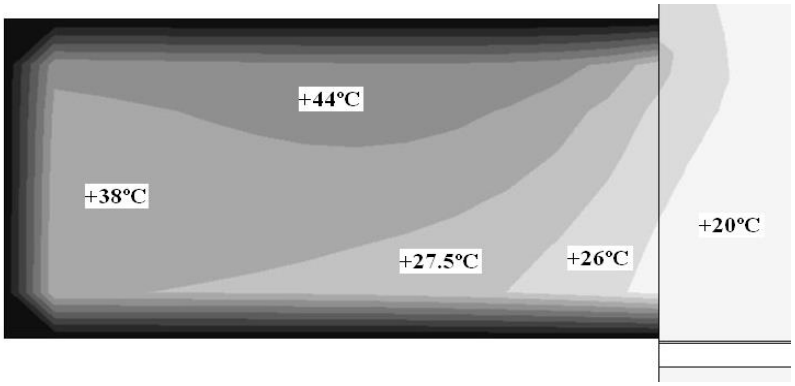
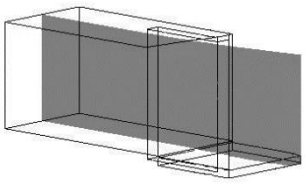


Figure 7.37 Illustration of the temperature gradients of the in- and out-flowing air through the chamber opening of the autoclave in Case 4, UDF-unit beside the opening. The air velocity (horizontal flow) is 0.45m/s.



Section in the middle of the autoclave chamber, see grey area.

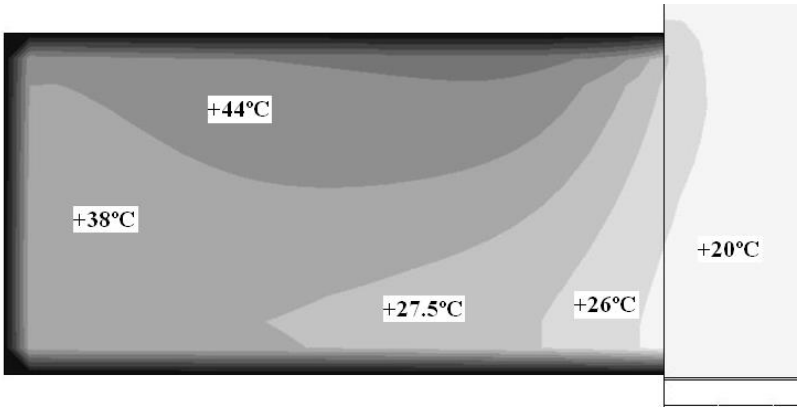


Figure 7.38 Illustration of the temperature gradients of the in- and out-flowing air through the chamber opening of the autoclave in Case 5, UDF-unit beside the opening. The air velocity (horizontal flow) is 0.90m/s.

7.5 Summary

The result of the temperature measurements and the visualization of air movements give information about the distribution of the in- and outflow of air through the opening of autoclaves. When the temperature of the air in the chamber is higher compared to the surrounding air (in the room) and the chamber door opens, the outflow will cover 1/3 of the opening area and the inflow 2/3. The outflow occurs in the upper part of the opening and has a higher air velocity compared to the inflow in the lower part of the opening.

The area for the outflow is slightly larger for the experimentally estimated air velocity profile compared to the CFD simulated. The difference in the height in the air velocity profiles between the experimentally and CFD simulation depends on that the experimental measurements are performed 5cm outside the chamber opening while CFD simulations show the results in the opening.

The CFD simulations show how the chamber and its opening can be protected from airborne contamination by using a UDF-unit. Both vertical and horizontal airflow from the UDF-unit give protection of the chamber opening of the autoclave, but horizontal airflow seems to be a more appropriate solution. The horizontal airflow maintains its velocity in front of the opening better compared to the vertical airflow. The faster reduction of the air velocities of the vertical airflow is caused by warm airflow rising from the chamber. The air temperature in the chamber decreases faster with horizontal airflow than with vertical airflow. If vertical airflow is required in front of an autoclave the airflow from the UDF-unit should preferably be 0.90m/s.

The airflow from the UDF-unit needs to be greater than the airflow through the opening of the autoclave. An estimated value for the UDF-unit should be 10-20% greater. During the design of the UDF-unit, the unloading procedure of the autoclave and the solution of the chamber door need to be considered. If the autoclave is unloaded manually and/or if the door to the autoclave opens out in the room, a higher airflow from the UDF-unit may be needed.

8 RESULT– CONTAMINATION OF THE OUTSIDE OF CLOTHING SYSTEMS

8.1 Validation of the Microbial Sampling Method

The results from the validation of the microbial sampling method using a dummy showed that the intended microbial sampling method for the observational study in the orthopedic surgical department was a reliable measurement method, see also Part 6.2.

A summary of the results is presented in Table 8.1. The results show in general a higher level of contamination on the surgical clothing system after exposure to an uncontrolled environment compared to before exposure. Only in a few cases do the results deviate and this may be due to differences in the way of dressing the dummy.

Table 8.1 Number of CFU per 24cm^2 and microbial mean values on the surgical clothing system on a test person and a dummy before and after exposure.

Sampling site on the clothing system	**Test person** ***Result before exposure/After exposure*** (number of CFU/24cm^2)			**Test dummy** ***Result before exposure/After exposure*** (number of CFU/24cm^2)		
	Day 1	**Day 2**	**Day 3**	**Day 1**	**Day 2**	**Day 3**
Shoulder	0/1	1/1	1/7	1/1	4/2	2/5
Upper arm	0/1	0/1	0/1	0/2	0/1	2/5
Breast	0/3	0/14	0/2	0/2	0/2	0/1
Thigh	0/7	0/10	0/2	0/2	0/2	0/0
Shin	0/0	1/0	2/1	0/0	0/0	0/1
Mean value	0/2.4	0.4/5.2	0.6/2.6	0.2/1.4	0.8/1.4	0.8/2.4

8.2 Observational Study in an Orthopedic Surgical Department

The results from the microbial sampling (number of CFU per 24cm^2) with regard to differences on the outside of surgical clothing before and after exposure, could be divided in three groups:

- Group 1
  The differences between the result before and after exposure: < 10 CFU/24cm^2 (average value)

- Group 2
  The differences between the result before and after exposure: 10-50 CFU/24cm^2 (average value)

- Group 3
  The differences between the result before and after exposure: > 50 CFU/24cm^2 (average value)

The results for each group are based on the differences in results between the average value for the sampling results on the four sampling locations on the surgical clothing system before and after exposure. Table 8.2presents the average result of all sampling sites on the clothing systems for the three groups.

Table 8.2 Microbial mean values of all sampling locations, number of CFU per 24cm^2, on the surgical clothing system before and after exposure and the differences.

	Number of CFU/24cm^2		
	Group 1: Difference < 10 CFU/24cm^2	**Group 2:** Difference 10-50 CFU/24cm^2	**Group 3:** Difference > 50 CFU/24cm^2
Mean results before exposure	27	44	30
Mean results after exposure	29	65	149
Difference	**2**	**21**	**119**

The distribution of test persons – number of test persons and their professional responsibilities - in each group is fairly even see Table 8.3.

Table 8.3 The distribution of test persons in respective result group and their professional responsibility.

Group	**Microbial contamination** (number of CFU/24cm^2)	**Number of test persons and their professional responsibility**
1	< 10	2 nurses 1 surgical nurse 1 anesthesia nurse
2	10-50	1 nurse 2 surgical nurses 2 anesthesia nurses
3	> 50	2 nurses 1 surgical nurse 1 anesthesia nurse

The individually results for the four locations on the surgical clothing system show the largest differences in results before and after exposure at the sampling locations breast and thigh, see results in Table 8.4.

Table 8.4 Microbial average values per sampling sites, number of CFU per 24cm^2 on the surgical clothing system before and after 1 day of exposure.

Sampling site on the clothing system	**Group 1:** ***Before exposure/ After exposure*** (number of CFU/24cm^2)	**Group 2:** ***Before exposure/ After exposure*** (number of CFU/24cm^2)	**Group 3:** ***Before exposure/ After exposure*** (number of CFU/24cm^2)
Shoulder	10 / 2 Difference: - 8	9 / 8 Difference: - 1	11 / 11 Difference: 0
Breast	**8 / 11** **Difference: +3**	**12 / 21** **Difference: +9**	**10 / 69** **Difference: +59**
Thigh	**5 / 13** **Difference: +8**	**15 / 27** **Difference: +12**	**9 / 60** **Difference: +51**
Shin	3 / 3 Difference: 0	6 / 7 Difference: +1	1 / 20 Difference: +19

All groups consisted of a mix of persons with different professional responsibilities, i.e. no differences in results seem to be based on professional responsibilities. However, there is a difference between the three groups in what type of environment the persons in each respective group have been working or visiting during their working day and the day the tests were performed, see Table 8.5.

Table 8.5 Description of the environment where the personnel included in the study have been working or visiting during the test.

Group	Environment
1	Mainly within the surgical department and in operating rooms 2 persons were exposed to uncontrolled environment for approx. 10-15 minutes
2	Mainly within the surgical department and in operating rooms (with exception of 1 person who was working in other premises within the surgical department) 2 persons were exposed to uncontrolled environment for approx. 10-15 minutes 1 person was exposed to uncontrolled environment for approx. 30 minutes
3	Within the surgical department and in operating rooms (with exception of 1 person who was working in other premises within the surgical department) 1 person participated in a meeting in an uncontrolled environment for approx. 1 hour 1 person was eating lunch in an uncontrolled environment for approx. 1 hour 1 person was exposed to uncontrolled environment for approx. 15 minutes 1 person was exposed to uncontrolled environment for approx. 30 minutes

Table 8.6 shows the airborne microbial levels in some of the environments the personnel visited during their working day.

Table 8.6 Airborne microbial levels within the surgical department and uncontrolled environments.

Environment	**Airborne microorganisms** (CFU/m^3)
Orthopedic operating room	Mean: 22 (min 4, max 96)
Anteroom to orthopedic operating room	Mean: 24 (min 6, max 39)
Corridors within the surgical department	Mean: 105 (min 54, max 224)
Adjacent room to preoperative transfer (uncontrolled environment just outside the surgical department)	200 (only one value)
Culvert (uncontrolled area)	Mean: 200 (min 85, max390)*

*The airborne microbial level in the culvert area increases during the day, i.e. higher values in the afternoon than in the morning.

8.3 Summary

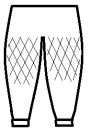
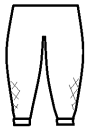
The results from the study clearly indicate a higher risk of microbial contamination of the surface of the surgical clothing system when the surgical staff visits uncontrolled environments outside the surgical department.

The study did not show any differences in result based on the professional responsibilities of the test persons. The main importance seems to be based on what type of environment the person has been visiting and the exposure time.

When the surgical personnel are visiting uncontrolled areas outside the surgical department, the behavior is different compared to the working procedure within the operating room. The difference in behavior in combination with an environment with higher level of airborne microorganism, the risk of microbial surface contamination of the surgical clothing system is clearly increased compared to work within the surgical department.

Only a limited area of the surgical clothing system has been microbial sampled. A theoretical calculation of microbial contamination has been performed based on the assumption that the measured values are in the same range on the concerned area. The calculation has been performed by measuring the respective area on the surgical clothing system and calculating the microbial contamination on the total measured area by using the microbial result from each of the sampling points after exposure. Table 8.7 presents the theoretical calculated results for the four sampling areas (shoulder, breast, thigh and shin).

Table 8.7 Results after exposure and estimation of the microbial contamination (total number of CFU) on specified surface (see check pattern area) of the surgical clothing system based on the results from each sampling location.

	Group 1		Group 2		Group 3	
	Result after exposure on sampling site, CFU per $24cm^2$	Total number of CFU on specified surface	Result after exposure on sampling site, CFU per $24cm^2$	Total number of CFU on specified surface	Result after exposure on sampling site, CFU per $24cm^2$	Total number of CFU on specified surface
Shoulder  A = $1000cm^2$	2	**83**	8	**333**	11	**458**
Breast  A = $2500cm^2$	11	**1146**	21	**2188**	69	**7188**
Thigh  A = $1750cm^2$	13	**948**	27	**1969**	60	**4375**
Shin  A = $1000cm^2$	3	**125**	7	**292**	20	**833**
Total number of CFU:		**2302**		**4782**		**12 854**

The calculation shows that the microbial contamination on the surface of the surgical clothing ranges from approximately 2 300 to 12 800 CFU. In this assumption, arms, most parts of the back and some parts of the surface of the trousers are not included. The real microbial contamination of the surgical clothing system may therefore be higher.

For some test persons, the result before exposure to the environment is unexpectedly high. This indicates that the changing procedure from personal clothing to the surgical clothing system needs to be reviewed.

9 RESULT– EVALUATION OF CLOTHING SYSTEMS

9.1 Source Strength during Ongoing Surgery

The measurements of airborne bacteria-carrying particles were performed in operating rooms during ongoing orthopedic surgery where the supply air devices were inclined screens, and the air movements could characterize as dilution mixing. Material and methods are described in Part 6.3. During the measurements the staff activity in the operating room was either high or low. High staff activity is during ongoing hip joint surgery and low staff activity is during other orthopedic surgery when the staff is more or less standing still.

The source strength for the clothing system of mixed material has been estimated based on the results from microbial measurements in operating rooms with high and low staff activity, see Part 9.2.

The source strength for the clothing system of Olefin has been evaluated without and with knee-length boots during ongoing surgery and with high staff activity, see Part 9.3.

9.2 Low and High Activity – Clothing System of Mixed Material

Tables 9.1 and 9.2 present the concentrations of airborne bacteria-carrying particles (aerobic CFU) and estimated source strengths for clothing system of mixed material during different orthopedic operations with high staff activity (Table 9.1) and low staff activity (Table 9.2).

Table 9.1 Concentration of aerobic CFU and estimated source strength for clothing system of mixed material during ongoing orthopedic operations with high staff activity in operating rooms with dilution mixing air.

OP no	Operating room		CFU concentration		Source strength*
	Air flow (m^3/s)	**No of persons** (no)	**Mean value** (CFU/m^3)	**Min – max** (CFU/m^3)	(CFU/s)
1	0.63	8	43	31-67	3.4
2	0.63	6	20	14-24	2.1
3	0.71	8	51.5	23-90	4.6
4	0.93	6	40	13-52	6.2
5	0.93	6	30.5	11-39	4.7
Source strength, grand mean value*: 4.2 CFU/s					

* Source strength values are given with one decimal.

Table 9.2 Concentration of aerobic CFU and estimated source strength for clothing system of mixed material during ongoing orthopedic operations with low staff activity in operating rooms with dilution mixing air.

OP no	Operating room		CFU concentration		Source strength*
	Air flow (m^3/s)	**No of persons** (no)	**Mean value** (CFU/m^3)	**Min – max** (CFU/m^3)	(CFU/s)
1	0.63	6	15	8-25	1.6
2	0.66	7	31	20-47	2.9
3	0.66	7	22.5	16-33	2.1
4	0.71	7	38.5	18-54	3.9
5	0.54	7	8	6-10	0.6
6	0.54	7	10	5-16	0.8
7	0.54	5	6	5-7	0.6
Source strength grand mean value*: 1.8 CFU/s					

* Source strength values are given with one decimal.

Tables 9.1 and 9.2 show that the source strength mean value during low staff activity is 43% than that of high staff activity. Furthermore, in Table 9.1 during high staff activity (hip joint surgery), the source strength mean value is calculated to 4.2 CFU/s. The difference in source strength due to activity level has been described by Ljungqvist and Reinmüller (2014), Ljungqvist et al (2014) and Ullmann et al (2017b). The source strength value of high activity (4.2 CFU/s) is in agreement with data given from hip joint surgery by Tammelin et al (2012).

9.3 Clothing System Olefin without and with Boots

Tables 9.3 presents the concentrations of airborne bacteria-carrying particles (aerobic CFU) and estimated source strengths for clothing system of Olefin without and with boots at different orthopedic operations with high staff activity.

Table 9.3 Concentration of aerobic CFU and estimated source strength for Olefin clothing system, without and with boots during ongoing orthopedic surgery with high staff activity in operating rooms with dilution mixing air and an airflow of 0.7m^3/s.

Air sample no	Without boots			With boots		
	No of persons	**Conc.**	**Source strength***	**No of persons**	**Conc.**	**Source strength***
	(No)	(CFU per m^3)	(CFU/s)	(No)	(CFU per m^3)	(CFU/s)
1	6	4	0.5	5	<2	<0.3
2	6	10	1.2	5	<2	<0.3
3	6	10	1.2	5	2	0.3
4	6	14	1.6	5	6	0.9
5	5	12	1.7	-	-	-
Mean value	5.8	10	1.2	5	<3	0.4

* Source strength values are given with one decimal.

Table 9.3 shows that the reduction of the number of aerobic CFU with boots compared to without boots is about 67%.

9.4 Summary

The result from the measurement of airborne bacteria-carrying particles in operating room during ongoing orthopedic surgery shows that the fabric of the surgical clothing system, the level of the staff activity (high or low) and the use of knee-length boots or not, are of high importance for the microbial air cleanliness in the operating room. Table 9.4 shows a summary of the results of the source strength for the three surgical clothing systems included in the measurement study.

Table 9.4 Summary of achieved results during ongoing orthopedic surgery for the source strength for different surgical clothing systems.

Clothing system	Source strength (CFU/s) Ongoing surgery
Mixed material (69% cotton, 30% polyester and 1% carbon fiber)	4.2 (high activity) 1.8 (low activity)
Olefin (98% olefin and 2% carbon) without knee length boots	1.2*
Olefin (98% olefin and 2% carbon) with knee length boots	0.4*

* Limited number of measurements, mainly high activity.

For the surgical clothing system of mixed material, the source strength value is 4.2 CFU/s during ongoing surgery with high activity and the value decreases to 1.8 CFU/s during low staff activity.

When the personnel are wearing the Olefin clothing system without and with knee length boots and the activity is mainly high, the source

strength is 1.2 CFU/s and 0.4 CFU/s respectively. The result shows that use of knee length boots considerable influence on the microbial air cleanliness in the operating room – the reduction of the number of airborne bacteria-carrying particles (CFU/m^3) with knee length boots compared to without is about 67%.

Figure 9.1 shows the agar plates used in the measurements of airborne bacteria-carrying particles with the Olefin clothing system; the upper four plates is showing the results from measurements with knee length boots and the plates below are the results without knee length boots.

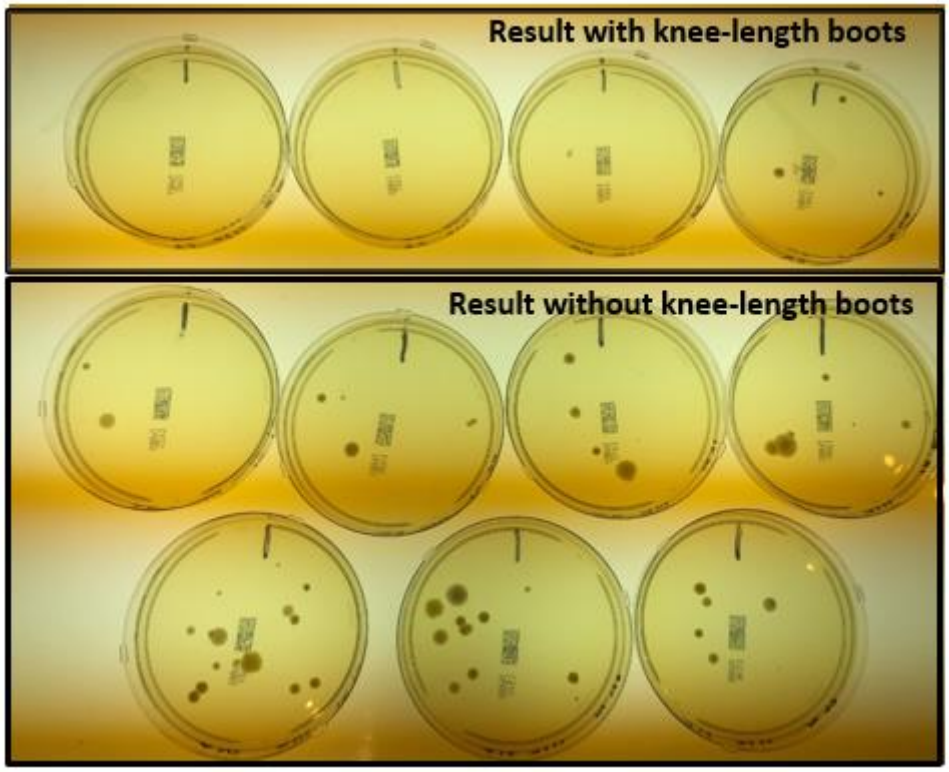


Figure 9.1 The agar plates used in the measurements of airborne bacteria-carrying particles in the operating room when the personnel are wearing the Olefin clothing system with and without the knee length boots.

10 RESULT– TISSUE AND CELLS ESTABLISHMENTS

10.1 Leakage Test of HEPA Filters

All unidirectional airflow units in the studied cell and tissue establishments described in Part 6.4 had leakages in the HEPA filter media and in the gaskets of the filter. The leakage varied from 0.015 to 100% (of the aerosol concentration on the upstream side) and was mainly located to the filter gasket. Figure 10.1 shows example of two filter gaskets in different unidirectional airflow units that did not fulfill the acceptance criteria of <0.01% leakage (ISO 14644-3).

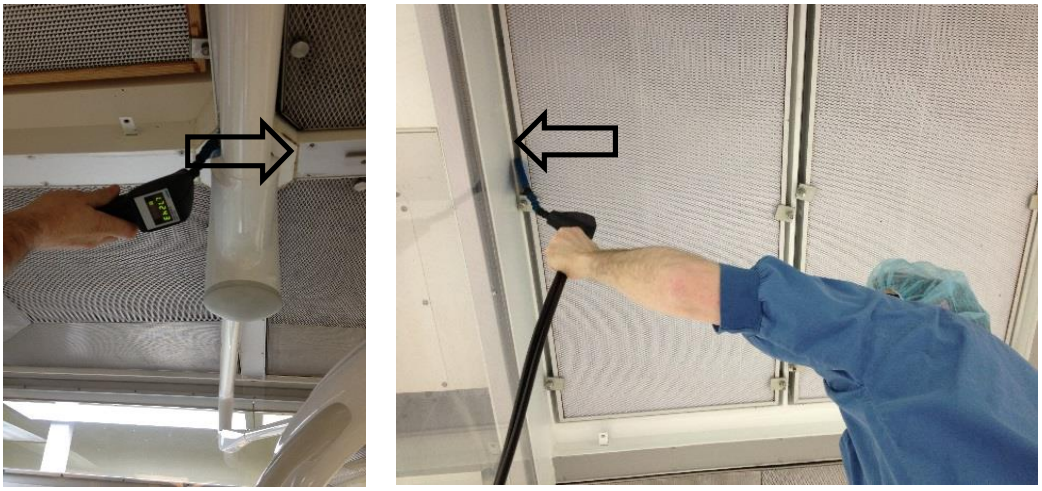


Figure 10.1 Pictures showing local leakages to filter gaskets in unidirectional airflow units that had leakages. The local leakage varied from 0.015 to 100%.

Due to considerable dilution, the leakages are not noticeable in the result from the airborne particle measurements, see further Part 10.4.

10.2 Visualization of Air Movements

Operating rooms with vertical and horizontal unidirectional airflow

The visualization of air movements at rest, demonstrated mainly unidirectional airflow within the units with vertical airflow, see schematically drawn pictures of the observed air movements in Figure 10.2.

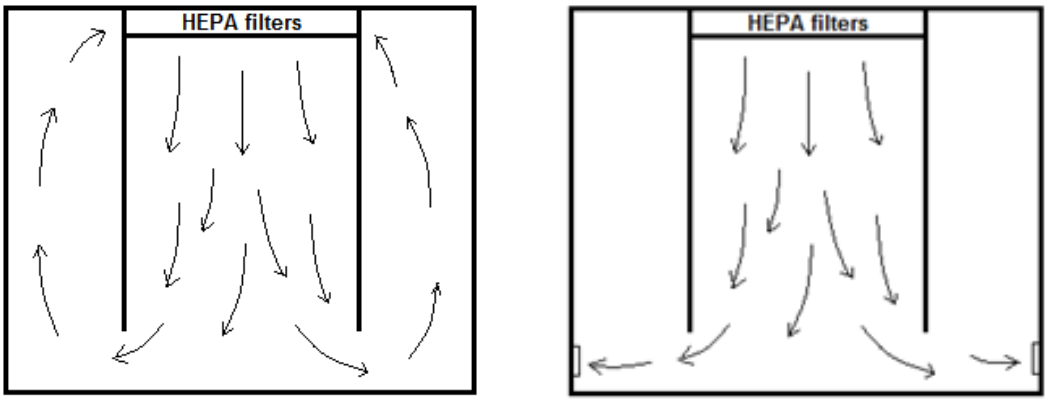


Figure 10.2 Schematically pictures showing the air movements at rest in vertical unidirectional units with high (to the left) respectively low (to the right) locations of the exhaust of the re-circulated airflow.

Visualization of the air movements within the area for the horizontal unidirectional unit at hospital E was not possible to perform because the room was needed for activities with higher priority.

The side walls of the vertical unidirectional units had two different designs:

- units with side walls going down almost to the floor
- units with short side walls (approx. 0.5-1m)

The unidirectional airflow was maintained further down within the area of the unit with longer side walls compared to the units with shorter side walls. Results of the visualization of the air movements for two different units, are shown in Figure 10.3.

Figure 10.3 Smoke showing the unidirectional airflow in a unit with short side walls (to the left) and a unit with longer side walls (to the right).

Vortices occur in the unidirectional airflow before and after obstacles, for example lighting equipment, see Figure 10.4.

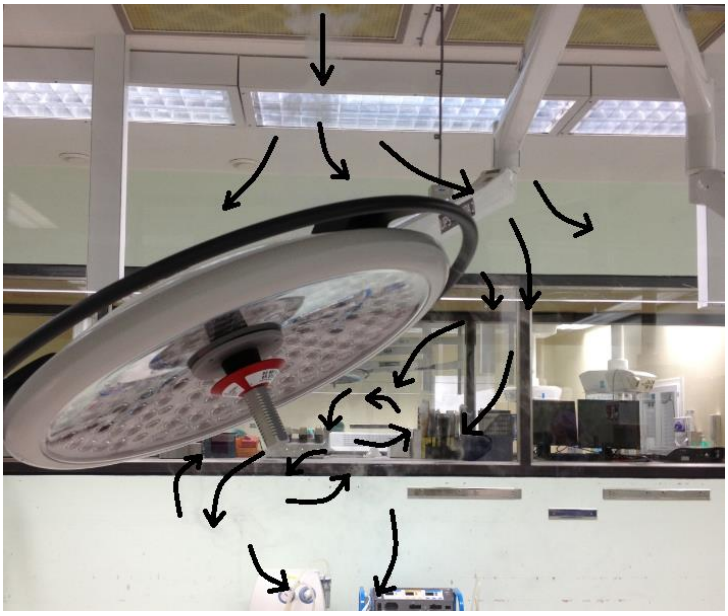


Figure 10.4 Disturbances(vortices) in the vertical unidirectional airflow above and below a surgical lamp.

Operating rooms with dilution mixing air

Some areas in the operating rooms with dilution mixing air were observed to have good dilution while other areas have regions with air almost standing still, see Figure 10.5. These regions have very low dilution and an increased risk for accumulation of contaminants. The regions mainly occur in areas with high occurrence of equipment and installations.

Figure 10.5 Example of a region in the room with air almost standing still (stagnation region).

Air moves along the floor and rises close to the operating table. A vortex occurs above the operating table, see Figure 10.6 and 10.7.

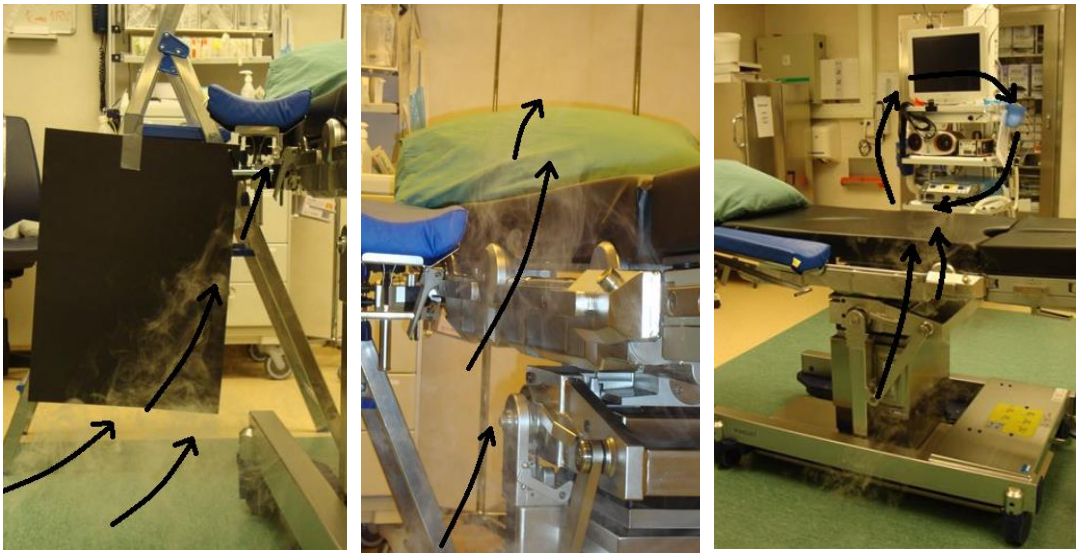


Figure 10.6 Pictures showing air movements close to the operating table and the vortex arising above the table.

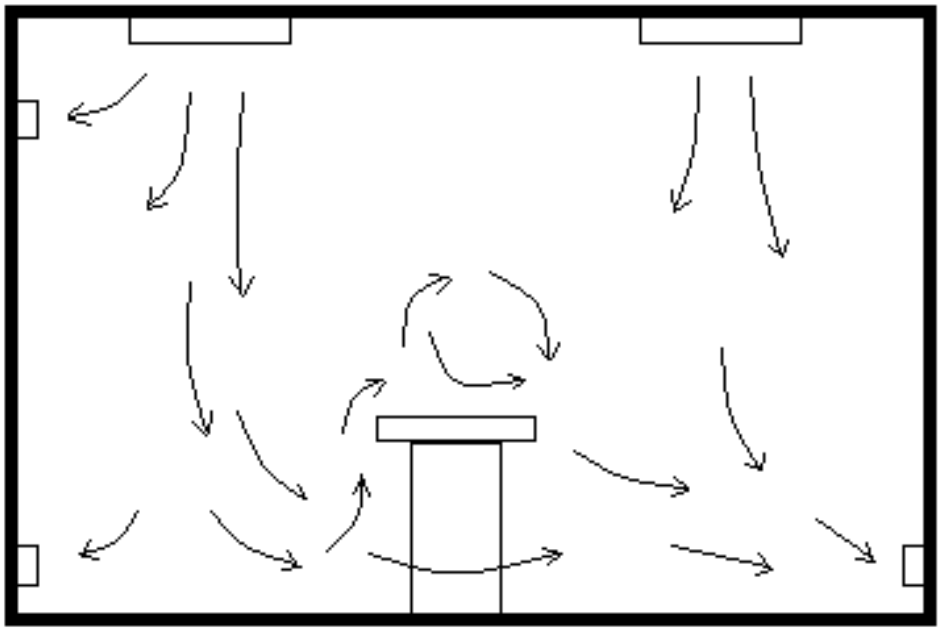


Figure 10.7 Schematically drawn picture showing the air movements close and above the operating table.

10.3 Airflow Directions / Differential Pressure

All studied operating rooms had a positive pressure difference to adjacent rooms. The pressure differences were in the range of 2-28 Pa.

10.4 Airborne Particles

Particle measurements were performed at rest in the cell and tissue establishment operating rooms described in Table 6.9. The number of sampling locations was 2-7 per operating rooms. Table 10.1 presents the results for the particle measurements and Table 10.2 gives a summary of the measured minimum and maximum result at rest based on the ventilation principle in the operating rooms.

Maximum permitted number of airborne particles per m^3 at rest:

Grade A	≥0.5µm: 3520	≥5µm: 20
Grade D	≥0.5µm: 3 520 000	≥5µm: 29 000

Table 10.1 Result of the particle measurements for each operating room at rest, 2-7 sampling locations per room.

Hospital	Operating room number, air flow m^3/s	Number of locations	Minimum and maximum number of airborne particles/m^3	
			≥ 0.5µm	≥ 5µm
A	A.1: Vertical UDF, 2.6m^3/s	2	<10/71	<10
B	B.1: Dilution mixing air, approx. 0.5m^3/s	7	188 484/233 576	424/1059
	B.2: Vertical UDF, 3.1m^3/s	1	<10	<10
	B.3: Dilution mixing air, approx. 0.5m^3/s	7	353 017/382 435	282/2119
	B.4: Dilution mixing air, approx. 0.5m^3/s	7	432 270/478 525	812/3143
	B.5: Dilution mixing air, approx. 0.5m^3/s	6	114 139/134 583	671/3283
C	C.1: Vertical UDF, 1.6m^3/s	2	106/1236	<10/71
D	D.1: Vertical UDF, 4.0m^3/s	3	<10	<10
	D.2: Dilution mixing air, 0.7m^3/s	2	33 936/40 294	<10/35
	D.3: Dilution mixing air, 0.7m^3/s	2	33 938/38 564	<10/141
E	E.1: Horizontal UDF, 4.3m^3/s	-*	-*	-*
	E.2: Dilution mixing air, 0.7m^3/s	-*	-*	-*

*Due to activities of higher priorities, operating rooms at hospital E were not available for measurements of airborne particles.

Table 10.2 Summary of the result of the airborne particle measurement at rest, based on the room air distribution system in the operating rooms.

Room air distribution system in the operating room	**Minimum and maximum number of airborne particles/m^3**	
	≥ 0.5µm	**≥ 5µm**
Operating rooms with vertical unidirectional airflow	<10/1236	<10/71
Operating rooms with dilution mixing air	33 936/478 525	<10/3283

The high airborne particle levels in some operating rooms, for example in the operating rooms at hospital B, indicate that the filters in the air supply system do not have adequate efficiency.

The detected leakages in the media and the gasket of the HEPA filters in unidirectional airflow units is not noticeable in the results due to considerable dilution.

10.5 Airborne Bacteria-Carrying Particles

Airborne bacteria-carrying particles were measured as CFU during ongoing surgery by active air sampling with a MAS-100® sieve sampler. Results for active air sampling are shown in Table 10.3. Table 10.4 gives a summary of the measured minimum and maximum result during ongoing surgery based on the ventilation principle in the operating rooms.

Recommended limits for of airborne bacteria-carrying particles per m^3 in operation:

Grade A < 1 CFU/m^3

Grade D < 200 CFU/m^3

Table 10.3 Results of active air sampling during ongoing surgery. Minimum and maximum of CFU/m^3 air at two sampling positions.

Hos-pital	**Operating room no.**	**Total number of samples**	**Active air sample** Minimum and maximum number CFU/m^3 air	
			Position 1: Close to the patient	**Position 2:**At the computer table
A	A.1: Vertical UDF, 2.6m^3/s	4	<1/25	14/19
B	B.1: Dilution mixing air, approx. 0.5m^3/s	4	56/102	26/48
	B.2: Vertical UDF, 3.1m^3/s	4	<1	24/27
	B.3: Dilution mixing air, approx. 0.5m^3/s	4	18/22	17/25
	B.4: Dilution mixing air, approx. 0.5m^3/s	4	25/74	38/56
	B.5: Dilution mixing air, approx. 0.5m^3/s	4	107/111	137/153
C	C.1: Vertical UDF, 1.6m^3/s	4	<1/8	12/13
D	D.1: Vertical UDF, 4.0m^3/s	4	<1/2	<1/5
	D.2: Dilution mixing air, 0.7m^3/s	4	5/9	24/26
	D.3: Dilution mixing air, 0.7m^3/s	4	5/9	5/16
E	E.1: Horizontal UDF, 4.3m^3/s	4	<1/5	4/78
	E.2: Dilution mixing air, 0.7m^3/s	4	3/5	2/9

Table 10.4 Summary of the result of the airborne CFU measurement, based on the room air distribution system in the operating rooms.

Room air distribution system in the operating room	**Minimum and maximum number of CFU/m^3**	
	Position 1: Close to the patient	**Position 2:** At the computer table
Operating rooms with vertical airflow	<1/25	<1/27
Operating rooms with dilution mixing air	3/111	2/153

The results from the performed measurements show varying levels of airborne CFU in the operating rooms during ongoing surgery. The different levels depend on:

- Air volume flow of the incoming air in the operating rooms. Seven of the operating rooms have dilution mixing air with a supply air volume flow of 0.4-0.7m^3/s while 5 operating rooms have unidirectional airflow units with an air volume flow of 1.6-4.3m^3/s.
- Different clothing systems and therefore different total source strength in the operating room. Personnel at hospital B is wearing clothing system of mixed material, while personnel at hospital D is wearing clothing system of disposable non-woven material. Clothing system of mixed material has a higher source strength value compared to the system of non-woven disposable material.

- Different activity level of the surgical staff during ongoing surgery. Some surgeries, for example hip joint surgery, requires higher activity from the personnel during the surgery which increases the source strength. Example of type of surgeries performed during the measurements are hip joint replacement, knee, shoulder, foot and thigh bone.
- Number of persons present during the ongoing operation. Due to type of operation, routines at the hospital etc. The number of persons present during ongoing operation varied between different surgeries and hospitals.
- Number of door openings during ongoing surgery. The procedure and discipline regarding door openings during ongoing surgery varies between different hospitals.

10.6 Microbial Surface Sampling

Microbial sampling was performed on floor and on horizontal surfaces within the operating room. The sampling was performed two times in each operating room; in the beginning and in the end of the working day. Table 10.5 presents the results for the microbial sampling on the floor and Table 10.6 the result for the horizontal surfaces.

Recommended limits for microbial surface (contact plates diameter 55mm) in operation:

Grade A < 1 CFU/plate

Grade D < 50 CFU/plate

Table 10.5 Results of microbial sampling on the floor at the start and at the end of the working day. The difference in average results between the start and the end of the working day is calculated.

	Start of the working day		**End of the working day**		**Difference in average results**
	Average (CFU per 24cm^2)	Min. / Max. value	Average (CFU per 24cm^2)	Min. / Max. Value	(CFU per 24cm^2)
A	71	39 / 110	29	21 / 39	-42
B	25	7 / 62	22	1 / 43	-3
C	51	42 / 60	65	48 / 82	+14
D	49	3 / 66	24	0 / 85	-25
E	17	6 / 46	15	4 / 28	-2

Table 10.6 Results of microbial sampling on horizontal surfaces in the five cell and tissue establishments. The difference in average results between the start and the end of the working day is calculated.

	Start of the working day		**End of the working day**		**Difference in average results**
	Average (CFU per 24cm^2)	Min. / Max. value	Average (CFU per 24cm^2)	Min. / Max. value	(CFU per 24cm^2)
A.	11	0 / 58	4	0 / 22	-7
B.	12	0 / 48	10	0 / 108	-2
C.	6	0 / 21	2	1 / 4	-4
D.	3	0 / 25	4	0 / 15	+1
E.	5	0 / 14	3	0 / 10	-2

The results from the microbial surface samplings on floor and horizontal surfaces within the operating rooms indicate that the cleaning procedures in the operating rooms performed by external personnel at the end of a working day are not as effective as the cleaning procedures performed by the personnel in the surgical ward between each surgery. For the majority of the sampling points, numbers of CFU (average value) on the surfaces are higher at the beginning of the working day compared to the results at the end of the day.

10.7 Summary

The operating rooms classified as tissue and cells establishment for bone tissue did not fulfill the requirements for grade A at the area for the handling of bone tissue regarding airborne particles (max number of particles ≥ 0.5µm 3 500/m^3 and ≥ 5µm 20/m^3), and for airborne bacteria-carrying particles (≤10 CFU/m^3).

The background requirement of grade D was fulfilled for airborne particles (max number of particles ≥ 0.5µm, 3 520 000/m^3 and ≥ 5µm, 29 000/m^3),and for airborne bacteria-carrying particles (≤200 CFU/m^3).

Most of the horizontal surfaces fulfilled the requirements for grade D (<50 CFU/contact plate) but not grade A (<1 CFU/contact plate). The surfaces within the operating room need to be classified if they should fulfill grade A requirement or grade D requirement, i.e., identify which surfaces are within the area for handling bone tissue (grade A) and which surfaces are within the background area (grade D).

Microbial surface sampling on the floor did not always fulfill the grade D requirements (< 50 CFU/contact plate).

The high-level of airborne particles in some operating rooms with dilution mixing air indicates inadequate HEPA filters in the supply air system or even absence of HEPA filter despite the information from the hospitals that the incoming air in all operating rooms is HEPA filtered.

Procedures for regular maintenance of HEPA filters in unidirectional airflow units, cleaning, door openings and number of persons present during ongoing surgeries need to be established or improved.

Procedures for regular cleaning of floors need to be improved.

Due to different conditions among the hospitals regarding for example clothing systems and air volume flows, it is not possible to determine the influence of the different layouts of operating rooms.

11 DOOR OPENINGS – THEORETICAL ASPECTS

11.1 Introduction

Door openings in operating rooms during ongoing surgeries may cause a contamination risk due to increased level of airborne microorganisms within the operating room. The number of airborne microorganisms coming from adjacent room to the operating room due to door openings, depends on:

- the airborne microorganisms concentration level within the adjacent room
- the temperature difference between the operating room and the adjacent room
- the door opening time
- the size of the door opening

Parts 11.4 and 11.5 present theoretical calculations of increased levels of airborne microorganisms within an operating room due to a door opening between the operating room and an adjacent room. Part 11.4 presents results when there is a temperature difference between the two different rooms and Part 11.5 without a temperature difference.

The calculations do not consider the source strength from an additional person entering the operating room, i.e. the calculated increased level of airborne microorganisms in the operating room is only due to the door opening. The entering person is an additional contamination source within the operating room and a correction of the total source strength and the microbial concentration needs to be performed.

The theoretical calculation can be used as a design base for needed cleanliness requirement of the adjacent rooms which the operating room has door openings between, to be able to fulfill the cleanliness requirement within the operating room during door openings.

11.2 Mathematical Treatment

The mathematical expressions for concentration of airborne contaminants in an operating room when a door between an adjacent room and the operating room is open, have been described by Ljungqvist et al (2009) and are discussed in Part 5.

The approximated expression for concentration of airborne contaminants in an operating room when a door between an adjacent room and the operating room opens is according to Equation (5.25)/(11.1):

$$c = c_0 + \frac{Q_d \cdot t_e \cdot (c_c - c_0)}{V} \qquad (5.25)/(11.1)$$

It should be noted that the approximate expression in Equation (5.25)/(11.1) does not consider the decay of the concentration due to the mechanical ventilation.

The expression for the equivalent door opening time (t_e) including opening time (t_0), open hold time (t_h) and closing time (t_c) of the door (the maximum door opening angle is $\pi/2$) is according to Equation (5.20)/(11.2):

$$t_e = t_h + \frac{2}{\pi}(t_0 + t_c) \qquad (5.20)/(11.2)$$

Observations in a surgical department have been performed to estimate equivalent door opening times. The studies have showed that the opening time (t_0) and the closing time (t_c) are about the same, 3 seconds, but the open hold time (t_h) can differ. Representative observations of open hold times have here been 6 seconds and 12 seconds. With the above given data used in Equation (11.2) the equivalent door opening times (t_e) could be calculated.

Observation 1 $t_e = 6 + 3.8 = 9.8 \approx 10$ seconds

Observation 2 $t_e = 12 + 3.8 = 15.8 \approx 16$ seconds

These estimations of the equivalent door opening time is in agreement with data described by Ljungqvist et al (2009) for equivalent door opening times referred as average and slow.

The theoretical calculations in Part 11.4 are based on the two equivalent door opening times 10 seconds and 16 seconds respectively.

The airflow through the doorway, due to temperature difference between the adjacent room and the operating room, is also discussed in Part 5 and is expressed according to Equation (5.17)/(11.3):

$$Q_d = C_d \frac{WH^{3/2}}{3} \left(g \frac{\Delta \rho_o}{\rho_{om}} \right)^{1/2} \qquad (5.17)/(11.3)$$

If the temperature difference between the operating room and the adjacent room is zero, approximated expression for concentration of airborne contaminants in the operating room when the door between the rooms open, is according to Equation (5.26)/(11.4):

$$c = c_0 + \frac{V_d}{V} c_c \qquad (5.26)/(11.4)$$

The typical exchange volume (V_d) when the door is moving is about 50% of the swept volume of the door (Ljungqvist et al (2009))which means:

$$V_d = 0.5 \cdot h \cdot \frac{\pi r^2}{4} \qquad (11.5)$$

where h = door height (m)
r = door swing radius (m)

11.3 Conditions for Calculated Cases

The calculated examples (cases) without and with a temperature difference between the operating room and the adjacent corridor are based on:

- an operating room with a volume of 125 m^3 and a mixing airflow distribution system
- the operating room is used for infection prone surgery
- two different sizes of the door opening
- two different equivalent door opening times *(only for the cases with temperature difference)*
- two different initial concentrations level of airborne microorganisms in the operating room
- four different concentrations of airborne microorganisms in adjacent room

An illustrated layout of the operating room, including data for the calculated examples, is shown in Figure 11.1. A summary of the conditions for the calculated cases, see Table 11.1 (cases with temperature difference) and Table 11.2 (cases with no temperature difference).

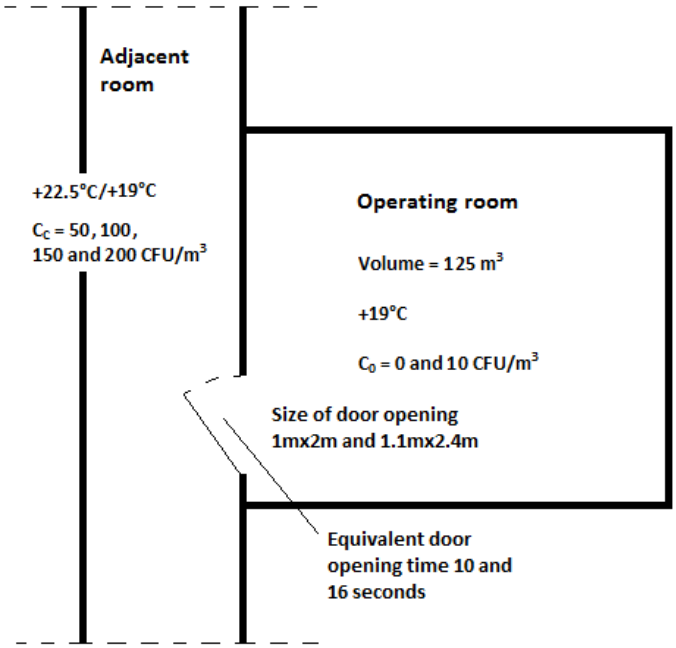


Figure 11.1 Layout for the operating room and the adjacent room including data for the calculated examples.

*Table 11.1 The conditions for the cases **with temperature difference**(Δt = 3.5°C) between the operating room and adjacent room. Calculated results according to values presented in Tables 11.3-11.6.*

Case	Result presented in Table	Door size (m^2)	Equivalent door opening time (s)	Initial concentration of CFU in the operating room (CFU/m^3)	Concentration level of CFU in adjacent room (CFU/m^3)
1	11.3	1x2	10 and 16	0	50, 100, 150 and 200
2	11.4	1x2	10 and 16	10	50, 100, 150 and 200
3	11.5	1.1x2.4	10 and 16	0	50, 100, 150 and 200
4	11.6	1.1x2.4	10 and 16	10	50, 100, 150and 200

*Table 11.2 The conditions for the cases with **no temperature difference**(Δt = 0°C) between the operating room and adjacent room. Calculated results according to values presented in Tables 11.7-11.8.*

Case	Result presented in Table	Door size (m^2)	Equivalent door opening time (s)	Initial concentration of CFU in the operating room (CFU/m^3)	Concentration level of CFU in adjacent room (CFU/m^3)
5	11.7	1x2	N/A*	0	50, 100, 150 and 200
6	11.7	1x2	N/A*	10	50, 100, 150 and 200
7	11.8	1.1x2.4	N/A*	0	50, 100, 150 and 200
8	11.8	1.1x2.4	N/A*	10	50, 100, 150 and 200

* The driven force for the air flow change through the door opening is the pumping effect of the door and the equivalent door opening time is there for not applicable for these cases.

11.4 Door Openings with a Temperature Difference between Rooms

By using Equation (11.3), the airflow through the door (in both directions) between the operating room and the adjacent room can be calculated. During a temperature difference of 3.5°C between the rooms, the airflow through the door openings are:

- Door opening 1mx2m 0.21m^3/s
- Door opening 1.1mx2.4m 0.30m^3/s

The increased value of airborne microorganisms within the operating room due to a door opening between the operating room and an adjacent room is calculated by using the Equations (11.1), (11.2) and (11.3).

Tables 11.3-11.6 and Figures 11.2-11.5 present results for four different cases (cases 1-4) with a temperature difference between the operating room and the adjacent room.

Case 1: Initial concentration of 0 CFU/m^3, door size 1mx2m, Δt = 3.5°C

Table 11.3 presents calculated values of airborne microorganisms in the operating room after one door opening (door opening size 1mx2m) between the operating room (initial concentration 0 CFU/m^3) and the adjacent room (concentration 50, 100, 150 and 200 CFU/m^3 respectively). The temperature difference between the rooms is 3.5°C. The result in Table 11.3 is illustrated in a graph, see Figure 11.2.

Table 11.3 Increased calculated values of airborne microorganisms in an operating room used for infection prone surgery and with an initial concentration of ***0 CFU/m^3, door size of 1mx2m and Δt = 3.5°C.***

Concentration of CFU/m^{3}in the adjacent room	**Increased value of CFU/m^3, ΔC*, in the operating room due to one door opening**	
	Equivalent door opening time 10 seconds (t_e)	**Equivalent door opening time 16 seconds** (t_e)
50	0.8	1.3
100	1.7	2.7
150	2.5	4.0
200	3.4	5.4

* Numbers are given to one decimal place.

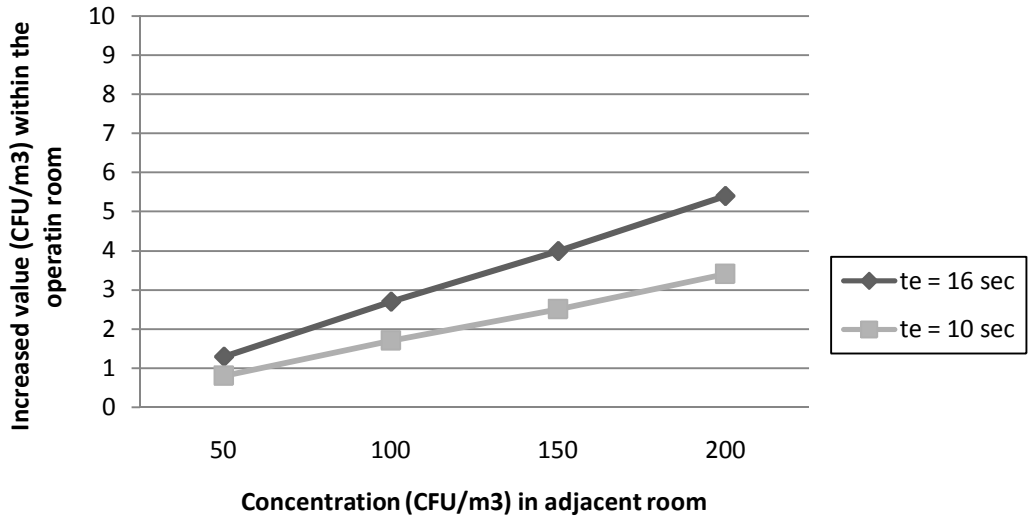


Figure 11.2 Graph showing increased values of airborne micro-organisms within the operating room due to a door opening between the operating room and an adjacent room. The temperature difference between the rooms is 3.5°C, the door opening size is 1mx2m and the initial concentration in the operating room is 0 CFU/m^3.

Case 2: Initial concentration of 10 CFU/m^3, door size 1mx2m, Δt = 3.5°C

Table 11.4 presents calculated values of airborne microorganisms in the operating room after one door opening (door opening size 1mx2m) between the operating room (initial concentration 10 CFU/m^3) and the adjacent room (concentration 50, 100, 150 and 200 CFU/m^3 respectively). The temperature difference between the rooms is 3.5°C. The result in Table 11.4 is illustrated in a graph, see Figure 11.3.

*Table 11.4 Increased calculated values of airborne microorganisms in an operating room used for infection prone surgery an initial concentration of **10 CFU/m^3, door size of 1mx2m and Δt = 3.5°C.***

Concentration of CFU/m^3 in the adjacent room	**Increased value of CFU/m^3, ΔC*, in the operating room due to door openings**	
	Equivalent door opening time 10 seconds (t_e)	**Equivalent door opening time 16 seconds** (t_e)
50	0.7	1.1
100	1.5	2.4
150	2.4	3.8
200	3.2	5.1

* Numbers are given to one decimal place.

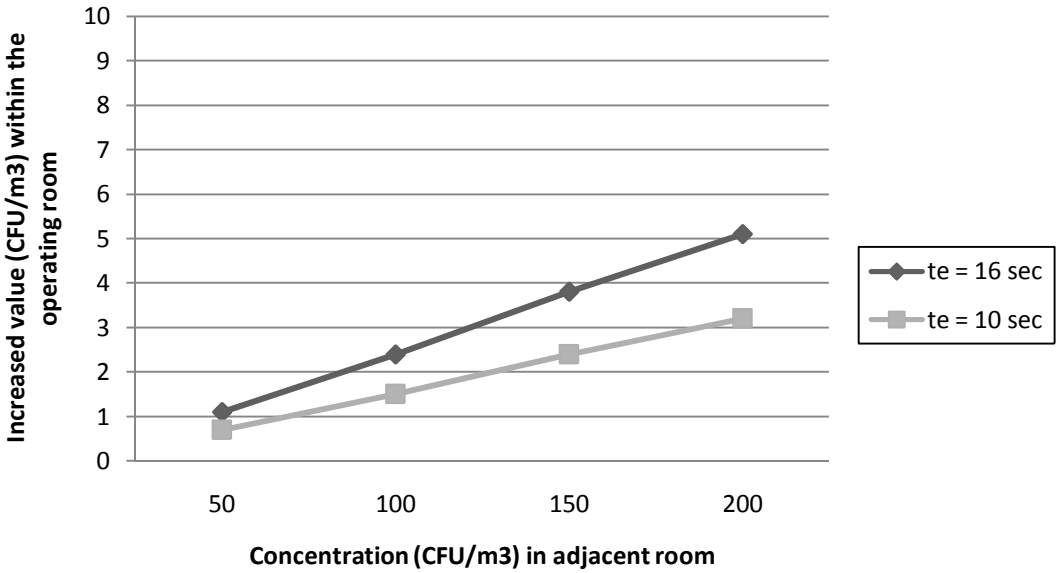


Figure 11.3 Graph showing increased values of airborne micro-organisms within the operating room due to a door opening between the operating room and an adjacent room. The temperature difference between the rooms is 3.5°C, the door opening size is 1mx2m and the initial concentration in the operating room is 10 CFU/m^3.

Case 3: Initial concentration of 0 CFU/m^3, door size 1.1mx2.4m, Δt = 3.5°C

Table 11.5 presents calculated values of airborne microorganisms in the operating room after one door opening (door opening size 1.1mx2.4m) between the operating room (initial concentration 0 CFU/m^3) and the adjacent room (concentration 50, 100, 150 and 200 CFU/m^3 respectively). The temperature difference between the rooms is 3.5°C. The result in Table 11.5 is illustrated in a graph, see Figure 11.4.

Table 11.5 Increased calculated values of airborne microorganisms in an operating room used for orthopedic prosthetic surgery an initial concentration of ***0 CFU/m^3, door size of 1.1mx2.4m and Δt = 3.5°C.***

Concentration of CFU/m^3 in the adjacent room	**Increased value of CFU/m^3, ΔC*, in the operating room due to door openings**	
	Equivalent door opening time 10 seconds (t_e)	**Equivalent door opening time 16 seconds** (t_e)
50	1.2	1.9
100	2.4	3.8
150	3.6	5.8
200	4.8	7.7

* Numbers are given to one decimal place.

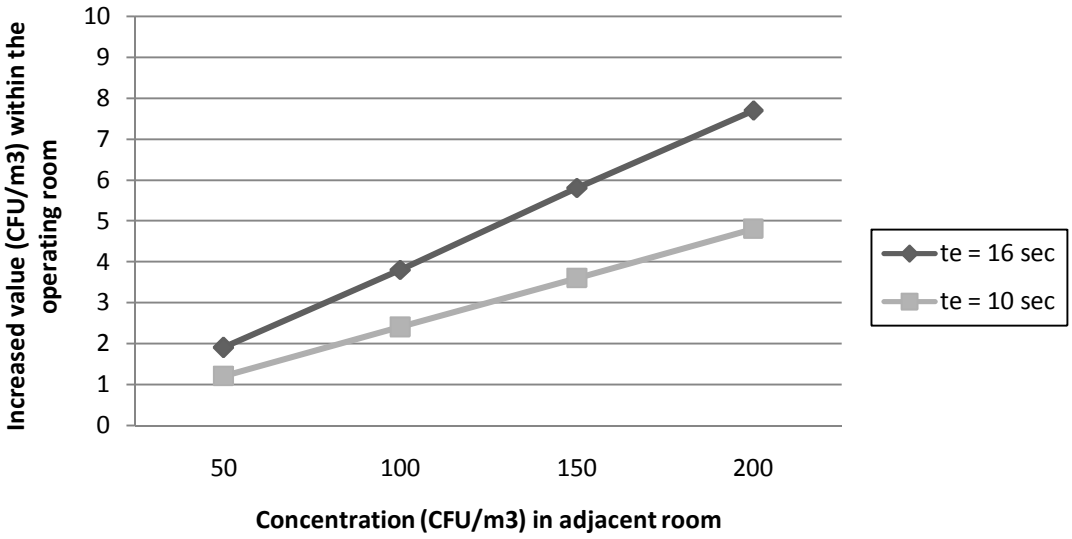


Figure 11.4 Graph showing increased values of airborne microorganisms in the operating room due to a door opening between the operating room and an adjacent room. The temperature difference between the rooms is 3.5°C, the door opening size is 1.1mx2.4m and the initial concentration in the operating room is 0 CFU/m^3.

Case 4: Initial concentration of 10 CFU/m^3, door size 1.1mx2.4m, Δt = 3.5°C

Table 11.6 presents calculated values of airborne microorganisms in the operating room after one door opening (door opening size 1.1mx2.4m) between the operating room (initial concentration 10 CFU/m^3) and the adjacent room (concentration 50, 100, 150 and 200 CFU/ m^3 respectively). The temperature difference between the rooms is 3.5°C. The result in Table 11.6 is illustrated in a graph, see Figure 11.5.

*Table 11.6 Increased calculated values of airborne microorganisms in an operating room used for infection prone surgery an initial concentration of **10 CFU/m^3, door size of 1.1mx2.4m and Δt = 3.5°C.***

Concentration of CFU/m^3 in the adjacent room	**Increased value of CFU/m^3, ΔC*, in the operating room due to door openings**	
	Equivalent door opening time 10 seconds (t_e)	**Equivalent door opening time 16 seconds** (t_e)
50	1.0	1.5
100	2.2	3.5
150	3.4	5.4
200	4.6	7.3

** Numbers are given to one decimal place.*

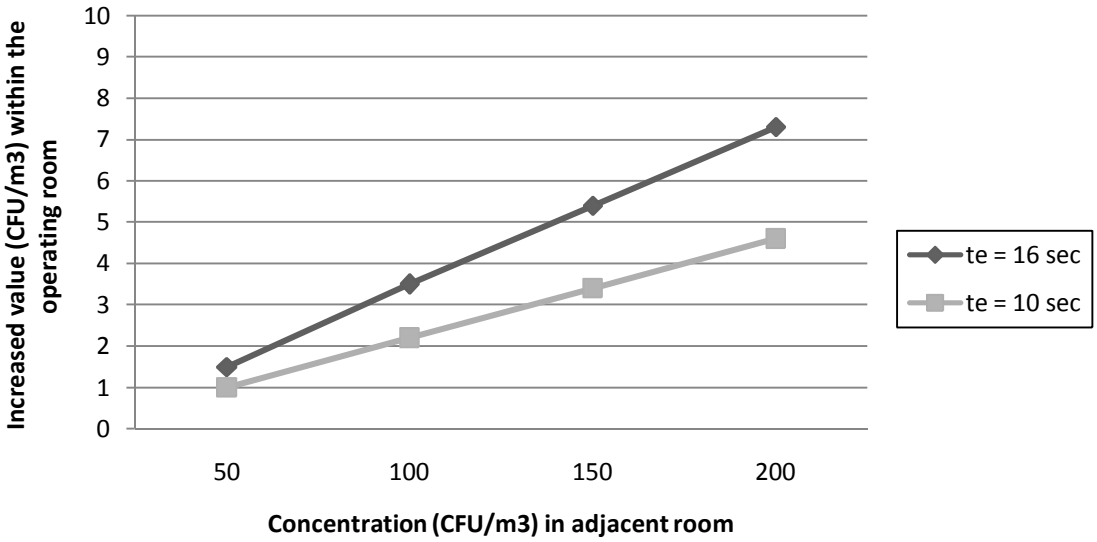


Figure 11.5 Graph showing increased values of airborne micro-organisms in the operating room due to a door opening between the operating room and an adjacent room. The temperature difference between the rooms is 3.5°C, the door opening size is 1.1mx2.4m and the initial concentration in the operating room is 10 CFU/m^3.

11.5 Door Openings without a Temperature Difference between Rooms

By using Equation (11.5) the air volume through the door opening between the operating room and the adjacent room with no temperature difference between the rooms, can be calculated. The driven force for the airflow through the opening is the pumping effect of the door.

With no temperature difference between the rooms, the exchange volumes (Equation (11.5)) for the two door openings are:

- Door opening 1mx2m $0.79m^3$
- Door opening 1.1mx2.4m $1.14m^3$

The increased value of airborne microorganisms in the operating room due to a door opening between the operating room and the adjacent room and during zero temperature difference between the rooms, is calculated by using Equation (11.4). The expression for the concentration difference in Equation (11.4) ($\Delta C = V_d \cdot C_c/V$) has the same value independent on the initial value of airborne microorganisms in the operating room. This means that the size of the door opening and the levels of airborne microorganisms in the adjacent room determine the increased value of airborne microorganisms in the operating room. The calculated result is there for the same for the Cases 5-6, and 7-8 respectively.

Tables 11.7 (Cases 5-6) and 11.8 (Cases 7-8) present the results for the four different cases with no temperature difference between the operating room and the adjacent room.

Case 5 and 6: Initial concentration of 0 and 10 CFU/m^3, door size 1mx2m, Δt = 0°C

Table 11.7 presents calculated values of airborne microorganisms in the operating room after one door opening (door opening size 1mx2m) between the operating room (initial concentration 0 and 10 CFU/m^3) and the adjacent room (concentration 50, 100, 150 and 200 CFU/ m^3 respectively). The temperature difference between the rooms is 0°C. The result in Table 11.7 is illustrated in a graph, see Figure 11.6.

*Table 11.7 Increased calculated value of airborne microorganisms in an operating room used for infection prone surgery an initial concentration of **0 and 10CFU/m^3, door size of 1mx2m and Δt = 0°C.***

Concentration of CFU/m^3 in the adjacent room	**Increased value of CFU/m^3, ΔC*, in the operating room due to one door opening**
50	0.3
100	0.6
150	0.9
200	1.2

** Numbers are given to one decimal place.*

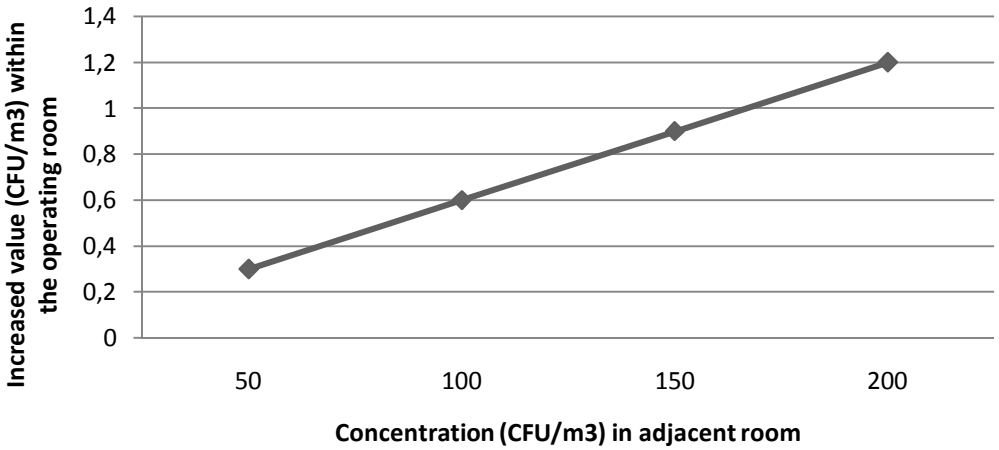


Figure 11.6 Graph showing increased values of airborne micro-organisms within the operating room due to a door opening between the operating room and an adjacent room. There is no temperature difference between the rooms, the door opening size is 1mx2m and the initial concentration in the operating room is 0 and 10 CFU/m^3.

Case 7 and 8: Initial concentration of 0 and10CFU/m^3, door size 1.1mx2.4m, Δt = 0°C

Table 11.8 presents calculated values of airborne microorganisms in the operating room after one door opening (door opening size 1.1mx2.4m) between the operating room (initial concentration 0 and 10 CFU/m^3) and the adjacent room (concentration 50, 100, 150 and 200 CFU/ m^3 respectively). The temperature difference between the rooms is 0°C. The result in Table 11.8 is illustrated in a graph, see Figure 11.7.

*Table 11.8 Increased calculated values of airborne microorganisms in an operating room used for infection prone surgery an initial concentration of **0 and 10CFU/m^3, door size of 1.1mx2.4m and Δt = 0°C.***

Concentration of CFU/m^3 in the adjacent room	**Increased value of CFU/m^3, ΔC*, in the operating room due to one door opening**
50	0.5
100	0.9
150	1.4
200	1.8

** Numbers are given to one decimal place.*

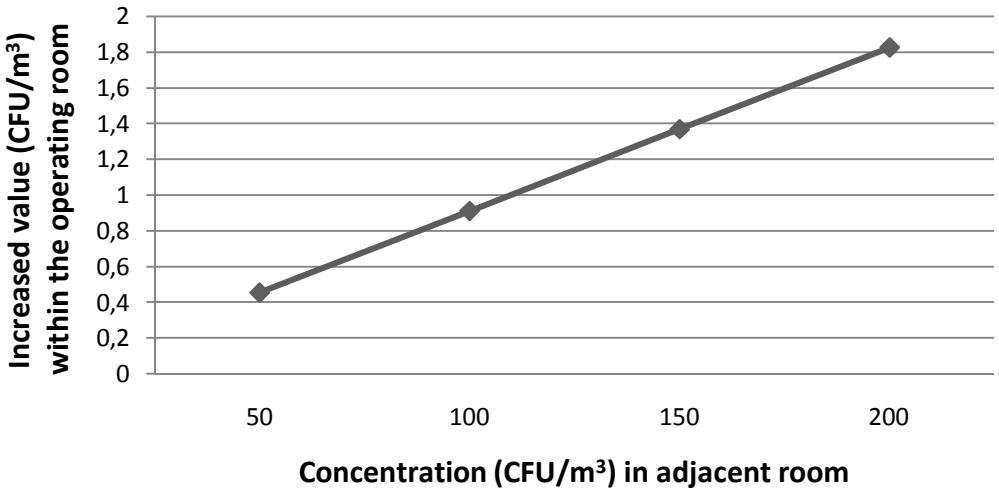


Figure 11.7 Graph showing increased values of airborne micro-organisms within the operating room due to a door opening between the operating room and an adjacent room. There is no temperature difference between the rooms, the door opening size is 1.1mx2.4m and the initial concentration in the operating room is 0 and 10 CFU/m^3.

11.6 Discussion

The theoretical calculated values of the increased numbers of airborne microorganisms in an operating room due to door openings, show that the concentration of airborne microorganisms in adjacent rooms may have negative consequences for the air quality in the operating room.

The increased values are based on only one door opening between the operating room and the adjacent room. If several door openings are performed during a short period, for example every two minutes, the numbers of airborne microorganisms will not be able to decrease to the initial level of airborne microorganisms between the different door openings. The initial concentration of microorganisms in the operating room will increase. The increase of the initial concentration depends on the recovery time (clean up period), i.e. the capacity of the ventilation system within the operating to reduce the concentration of airborne microorganisms.

Table 11.9 specifies the recovery time (clean-up time) for the operating room (in the theoretical calculated cases) for different values of the supply airflow of the ventilation system. The recovery time starts after the door is closed and is depending on the air change rate in the room. The values of the supply airflow given in Table 11.9 are common values for operating rooms in Sweden. The theoretical recovery times for reduction 100:1 (according to ISO 14644-3) by using Equation (5.13) are shown in Table 11.9. Due to low concentrations of airborne microorganisms, the reduction of 10:1 is also given.

Table 11.9 Recovery time within the operating room for different values of the supply airflow. (Room volume 125m^3)

Supply airflow (m^3/s)	**Air changes/hour**	**Recovery time, 100:1** (min)	**Recovery time, 10:1** (min)
0.56	16.1	17.2	8.6
1.0	28.8	9.6	4.8
1.5	43.2	6.4	3.2
2.0	57.6	4.8	2.4
3.0	86.4	3.2	1.6

Figure 11.8 illustrates how the concentration level may vary in the operating room due to repeatedly door openings (every two minutes) between the operating room and adjacent room. The graph in Figure 11.8 is based on the conditions for the operating room in case 4 (an equivalent door opening time of 16 seconds and 100 CFU/m^3 in adjacent room) and a supply airflow of 0.56m^3/s. The graph is showing rectilinear approximation of the real case and the line is there for dashed for the decay phase. The real decay phase is calculated by Equation (5.7). The approximated expression for concentration of airborne contaminants in the operating room, Equation (11.1), does not consider the decay of the concentration due to the airflow of the ventilation, which here gives an overestimation of the concentration less than 3 percent compared to the values given by the theoretical expression in Equation (5.23).

The result shows that the supply airflow of 0.56m^3/s will not be able to reduce the concentration of airborne microorganisms to the initial concentration between the door openings if a door opening occur every two minutes. The concentration will increase a small amount after each door opening.

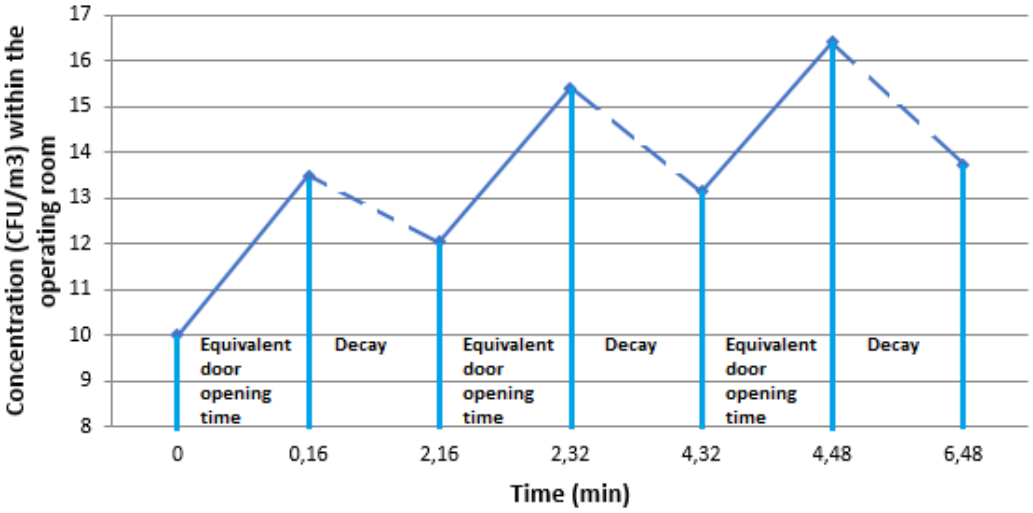


Figure 11.8 Graph showing the increased concentration of airborne microorganisms in the operating room due to a door opening every two minutes between the operating room and the adjacent room when the operating room has a supply airflow of 0.56m^3/s. Initial concentration within the operating room before the first door opening is 10 CFU/m^3 and the concentration within the corridor is 100 CFU/m^3. (Case 4: Δt=3.5°C, t_e=16 sec.)

Table 11.10 presents theoretical calculated values of the increased concentration of airborne microorganisms in the operating room for case 4 (Δt = 3.5°C, an equivalent door opening time of 16 seconds and a door opening size of 1.1x2.4m), after three door openings with two minutes between the openings and at two different supply airflows; 0.56m^3/s and 2.0m^3/s. The results show that the increased concentration in the operating room is 30-40 percent lower for the case with the supply airflow of 2.0m^3/s due to a higher air change rate and a faster recovery time (clean up time) compared to the case with the supply airflow of 0.56m^3/s. Even if the increase is less, the calculations clearly indicate the need of reducing the frequency of door openings also when the supply airflow is high.

Table 11.10 Comparison of increased values of initial concentration within the operating room after three door openings (two minutes between each door opening) for two different supply airflows in the operating room and for four different concentration within the adjacent room. Values according to case 4.

Concentration within adjacent room (CFU/m^3)	**Increased value of initial concentration within the operating room after three door openings (two minutes between each door opening)** (CFU/m^3)					
	Supply airflow 0.56m^3/s			**Supply airflow 2.0m^3/s**		
	Door-opening no 1	**Door-opening no 2**	**Door-opening no 3**	**Door-opening no 1**	**Door-opening no 2**	**Door-opening no 3**
50	1.5	2.4	2.9	1.5	1.7	1.8
100	3.5	5.4	6.4	3.5	3.9	4.0
150	5.4	8.4	10.1	5.4	6.1	6.2
200	7.3	11.4	13.7	7.3	8.4	8.5

The calculations of the four different cases with a temperature difference between the operating room and the adjacent room (Case 1-4), show that the opening time of the door and the size of the door opening have significant impact of the result:

- the longer equivalent door opening time (16 seconds) gives approximately 60 percent higher concentration of airborne microorganism within the operation room compared to the shorter equivalent door opening time (10 seconds)

- approximately 40-50 percent more airborne microorganism comes from the adjacent room into the operating room through the larger door opening area (1.1mx2.4m) compared to the smaller opening (1mx2m)

Comparison between the cases without and with a temperature difference between the operating room and the adjacent room, shows that the increased concentration of airborne microorganisms within the operating room due to door openings is for the cases without a temperature difference approximately 25 percent of the result for the cases with a temperature difference.

SIS-TS39:2015 (2015), gives guidance regarding design values for the concentration of airborne microorganisms within adjacent room to operating rooms. The guidance value is ≤100 CFU/m^3. When designing facilities for operating departments it is important to analyze the flow of personnel, material and patients within the department and establish a user requirement specification as a basis for the design of the facilities. A thorough analyze of the different flows in combination with a risk assessment, gives valuable information to be able to perform a correct design of the facilities. For example, if the analyze and the risk assessment establish that doors to the operating rooms need to be open during ongoing surgeries, the cleanliness requirement in adjacent areas must be higher compared to closed operating rooms. Even airlocks may be needed if adjacent rooms are corridors with risk for high concentrations of airborne contaminations due to high personnel flow. Furthermore, the analyze may give information about needed door sizes. By reducing the size of the door openings and only have larger door where it is really necessary, for example where flow of large equipment and patients will be performed.

11.7 Summary

The calculations show the necessity to eliminate, or at least reduce, door openings between the operating room and the adjacent room during ongoing infection prone surgery.

If door openings are needed during ongoing surgeries, the inflow of airborne microorganisms from adjacent rooms into the operating room can be reduced by:

- Minimize (when possible) the temperature difference between the operating room and the adjacent rooms
- Minimize the door opening time
- Decreasing the influence of door openings by designing door sizes for its correct use (only have larger door openings where transport of large equipment and patients will be performed)
- Use of airlocks

The maximum allowed level of concentration of airborne contamination in the adjacent areas needs to be based on the need of door openings during ongoing surgery and analysis of the flow of personnel, material and patients within the department to establish knowledge of the load of contamination sources within the adjacent areas. The conclusion may be, for example, that airlocks are needed due to high concentrations of contaminants or that the guidance value of ≤100CFU/m^3 (according to SIS-TS39:2015, (2015)) is adequate for the assessed operating department.

12 DISCUSSION AND CONCLUSION

12.1 Discussion

An environment with cleanliness requirement, demands high focus on the complete design including established procedures, environmental monitoring and maintenance controls during use or regular production. Contamination control requires an understanding of all different parameters that makes a clean environment possible and maintained over time. If even one parameter is failing, the cleanliness requirement may not be fulfilled for the environment and the patient safety may be reduced. Figure 12.1 gives example of parameters that need high focus and knowledge to meet the cleanliness requirement for an environment.

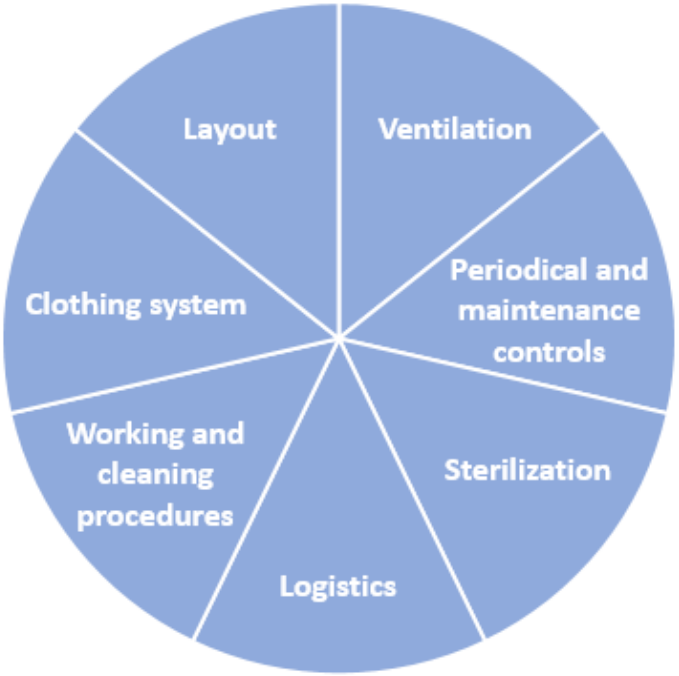


Figure 12.1 Picture showing example of parameters that are of high importance to be able to create an environment with high cleanliness requirement.

Measurements, observational studies, and theoretical calculations within this work include several of given parameters and the results highlight specific areas of interest to contamination control:

Autoclaves

When chamber door to an autoclave is open after a process run, the temperature in the chamber is usually higher than the ambient room air. The temperature differences give rise to an outflow of air in the upper part of the chamber opening and inflow in the lower part, see Figure 12.2.

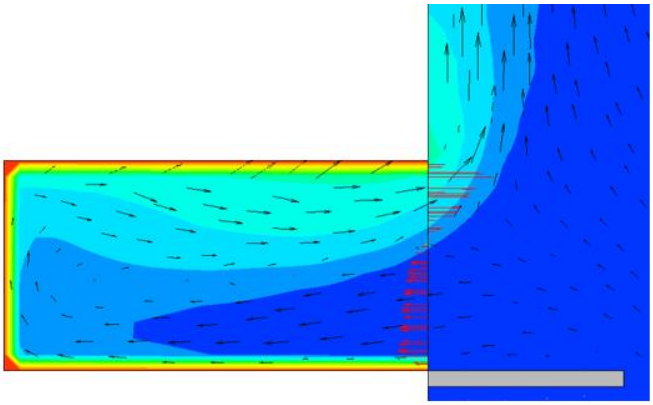


Figure 12.2 Airflow over an opening of an autoclave during a temperature difference between the air in the chamber and the ambient room air (the air in the chamber has a higher temperature compared to the surroundings).

The inflow of air covers 2/3 of the opening area and the outflow 1/3, which gives that the velocity is higher for the outflow compared to the inflow. Using the value 0.5 of the discharge coefficient makes it possible to calculate the airflow through the openings of autoclaves when the temperature difference with the ambient room air is 20-80°C.

To design a well-functioning UDF-unit in order to protect openings of autoclaves, the airflow from the UDF-unit should be greater than the airflow through the openings. An estimated value for the airflow from the UDF-unit should preferably be 10-20% greater than that of

the calculated airflow through the chamber opening. If the unloading is handled manually or if the chamber door opens out in the room, the airflow from the UDF-unit should be even greater compared to autoclaves that are loaded automatically or are equipped with sliding doors.

The results from the experimental tests verify the results of the CFD simulation. CFD is a valuable tool for studying design changes. The LR-method gives valuable information of potential contamination risks and is a useful method for verifying the design.

Due to contamination risk of reusable instruments and equipment in autoclave chambers during loading and unloading in sterile supply centers, the premises for assembly and packing area (loading area) and the sterile storage (unloading area) need to have increased cleanliness. The supply air volume flow in these rooms should to be HEPA-filtered and create a positive pressure difference to the surroundings. The rooms should have cleanroom standard and separated airlocks for personnel and material. The staff should wear dedicated clothing system suitable for the cleanliness requirement.

Contamination of the outside of clothing systems

During visits in uncontrolled environments outside the surgical department, the surgical staff risk to contaminate the outside surface of the surgical clothing system. The level of the contamination of the surface depends on type of environment and the exposure time. The difference in behavior outside the surgical department in combination with an environment with higher level of airborne microorganism, the risk of microbial surface contamination of the surgical clothing system is clearly increased compared to work within the surgical department. A theoretical calculation based on the result of measured microbial contamination level of four areas on the surface on the surgical clothing system, the total microbial contamination on the surface of the surgical clothing system is ranging from approximately 2300 to 12 800 CFU. In this assumption, arms, most part of the back and some parts of the surface of the

trousers are not included. The real microbial contamination of the outside of surgical clothing system may therefore be higher.

Some observations

Changing procedure needs to be reviewed and locker rooms must be of sufficient size and well planned to be able to create an environment with decreased risk for contamination during change of clothing. Figures 12.3 and 12.4 show photos from a locker room at a hospital with several risks for contamination during the changing procedure; exposed and contaminated soles of shoes, old clothes, forgotten private belongings and garbage.

Figure 12.3 Storage of shoes in a locker room within a hospital.

Figure 12.4 Photos of the inside of two cabinets in a locker room within a hospital.

Evaluation of clothing systems

The fabric and the design of the clothing system affect the value of the source strength as well as the activity level of the personnel during the performance of the surgery. For the surgical clothing system of mixed material, the source strength value is 4.2 CFU/s during ongoing surgery with high activity and the value decreases to 1.8 CFU/s during low staff activity. If the personnel wear the Olefin clothing system without and with knee length boots, see Figure 12.5, and the activity is mainly high, the source strength is 1.2 CFU/s and 0.4 CFU/s respectively. The result shows the major impact of knee length boots on the value of the clothing system source strength and its importance to decrease the airborne contaminants from personnel to the surroundings. The reduction of the number of airborne bacteria-carrying particles (CFU/m^3) with knee length boots compared to without is about 67%.

Without knee length boots *With knee length boots*

Figure 12.5 Pictures showing Olefin clothing system without and with knee length boots.

Tissue and cells establishments

Operating rooms used for the procedure of handling human tissue and cells did not fulfill the requirements for grade A (according to EU GMP Annex 1, (2008)) at the area for handling bone tissue regarding airborne particles and airborne bacteria-carrying particles. The background requirement of grade D (according to EU GMP) is fulfilled for airborne particles and airborne bacteria-carrying particles. These operating rooms also need to fulfill the recommendation of airborne

microbial cleanliness in ultraclean air operating rooms according to SIS-TS 39:2015(2015) of maximum 10 CFU/m^3within an operating room used for orthopedic surgery. Most of the operating rooms did not fulfill this requirement.

The study especially proves the necessity of improvement in working and cleaning procedures, maintenance controls, and basic understanding of the room air distribution system prerequisites to function in a correct way.

The result from the microbial surface sampling shows that the cleaning procedures in the operating rooms performed by external personnel at the end of a working day is not as effective as the cleaning procedures performed by the personnel from the surgical department between each surgery. The levels of microorganisms on floors and horizontal surfaces within the operating room, were in majority higher at the beginning of the day compared to the end of the day (sampling performed before the external personnel starts to clean). Figure 12.6 shows pictures of visible contamination within an operating room at the beginning of a working day.

A footprint at the base of the surgical table.

Contamination after wiping the floor within the operating room.

Figure 12.6 Contamination within an operating room at the beginning of a working day.

The visualization of air movements within operating rooms with turbulent mixing air showed areas with good dilution while other areas showed stagnation regions or vortices with an increased risk for accumulation of contaminants. An observed example of an area with a vortex and an increased risk for contaminants, is above the operating table, see Figure 12.7. Air moves along the floor and arises close to the operating table and creates a vortex above the operating table.

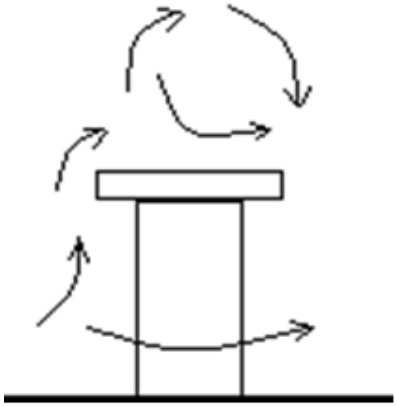


Figure 12.7 An observed vortex above an operating table.

To increase the contamination control, the handling of bone tissue could be performed in a clean environment by using a local UDF-unit within the operating room.

Door openings (theoretical aspects)

Door openings between operating rooms and adjacent rooms during ongoing surgery may cause a contamination risk; airborne microorganisms may come from adjacent room during door openings and increase the level of airborne microorganisms in the operating room. If door openings are necessary during ongoing surgery, it is important to decrease the number of door openings and the opening time.

Other significant factors affecting the risk of increased level of airborne microorganisms in the operating room due to door

openings, are the concentration of airborne microorganisms in adjacent rooms, temperature difference between the rooms, and the size of the door opening. In addition to decrease the number of door openings and the door opening time, it is important to strive for low concentration of airborne microorganisms in adjacent areas, minimize the temperature difference between the rooms and the size of the door opening.

The theoretical calculations show that if there is a high frequency of door openings, the number of airborne microorganisms in the operating room will not decrease to the initial level of airborne microorganisms in the operating room.

By analysis the flow of personnel, material and patients within the operating department, knowledge of contamination sources within adjacent rooms will be established. The analysis can thereafter be used as a basis for establishing procedures regarding door openings and to identify if airlocks between operating room and adjacent rooms are needed.

Contamination control in hospital versus pharmaceutical industry

High cleanliness is a necessity both within hospital environments and pharmaceutical production areas to ensure safe conditions for the patients.

The distinction between the branches is the consequences of one single failure or accident. For the pharmaceutical industry one single failure might affect a large number of persons whereas a failure in the operating room might affect only one person. But lack of necessary cleanliness may cause serious harm to many patients within the healthcare and it is always a tragedy for each single person regardless how many persons suffering from a failure.

The background environment for aseptic preparation and filling (grade B) within the pharmaceutical industry and the environment

for ultraclean operating rooms has the same recommended limits for microbial contamination; ≤ 10 CFU/m^3.

A common remark within the hospital is that it is not possible to apply cleanroom requirements and transfer experience and knowledge from pharmaceutical production to the ultraclean air operating room. There are too many parameters that are different between e.g., the layout, surface materials, type and amount of equipment in the room, the quantity of personnel present in the room, gowning requirement, and working procedures are all parameters that today differ between the areas. But the fundamental conditions are the same for both type of clean environments and processes; they require high levels of cleanliness (the microbial air cleanliness requirement/recommendation are the same) and the procedures (infection prone surgery and aseptic sterile production)can both be defined as a kind of aseptic processing. The question should therefore instead be; may the safety of the patient within the ultraclean air operating room increase by adopting appropriate cleanliness knowledge and experience from the pharmaceutical industry?

The requirements for the pharmaceutical industry have been adopted for one kind of processes within hospitals; the areas used for the processing of human tissues and cells should fulfill the requirements for airborne particles and microorganisms according to limits specified in the EU GMP (2008) according to European Directive (2004) and SOSFS (2009).

It seems to be a general reluctance within the hospital to adopt new procedures. Changes and upgrading within the pharmaceutical industry are based on risk assessment and the changing process is usually fast. Within hospitals, changes and upgrades have often an evidence-based approach and the changing process seems to be slower than that of pharmaceutical industry.

Within the operating rooms, trolleys not needed for the forthcoming operation and other mobile furniture are sometimes placed improperly due to the function of the room air distribution system; exhaust air devices are partly blocked, see Figure 12.8, and the

dilution principle within the room is disturbed. This can create areas with air standing still or vortices within the operating room causing contamination risks.

Figure 12.8 Blocked exhaust air devices within an operating room.

The responsibility for some of the needed maintenance and periodical tests within the operating room, and for the room air distribution system, seems in some cases be undefined and the knowledge of the installations needs to be improved. The leakages in the HEPA filters in unidirectional airflow units, and the lack of knowledge if HEPA filters are installed in the duct system or not, clearly indicate needed improvement in this area.

Other examples of inadequacies within the maintenance area, are shown in Figure 12.9.

The procedure regarding intake of materials and goods into the surgical department may also need to be reviewed, and what is allowed to bring in to the department as well. For example, cardboard boxes should be left outside the department and drinks and foods should only be consumed in dedicated rooms. Figure 12.10 shows a drink found in a storage room within the surgical department.

An almost "collapsed" pre-filter in a unidirectional airflow

Not well-functioning storage of filters for maintenance

Visible electrical wirings in a hole in wall

Damaged door

Molds on a barrier wall at a horizontal unidirectional airflow unit

Broken exhaust air device

Figure 12.9 Pictures showing different examples of inadequacies within the maintenance area that can cause contamination risks within the operating room.

Figure 12.10 A drink found in a storage room within a surgical department.

12.2 Conclusions

The performances and the results of the measurement studies within this work, have established conclusions regarding the understanding of air movements risen due to temperature differences between a process equipment (autoclave) and the surroundings, surgical clothing system, fulfillment of environmental requirements within tissue and cells establishments and door openings in operating rooms. The following conclusions have been established based on the results from observations and measurements:

Autoclaves

- When the temperature in the chamber is higher than the surrounding air, the outflow will occur in the upper part of the chamber opening and the inflow in the lower part.
- The inflowing air covers 2/3 of the opening area of the autoclave and the out-flowing air covers 1/3. The air velocities are higher for the outflow compared to the inflow.
- The discharge coefficient, C_d, has a value of 0.5 when the temperature difference is 20 to 80°C between the air in the chamber and the surrounding air.
- Chamber openings with outflow in the upper part are preferably protected by a UDF-unit. A UDF-unit with a horizontal airflow (approx. 0.45m/s) is preferable. A UDF-unit with vertical airflow is a possible solution but need a higher air velocity (approx. 0.9m/s).
- The assembly and packing area and sterile storage within sterile supply centers need to have cleanroom standard to reduce contamination risks of reusable instrument and equipment.

Contamination of the outside of clothing systems

- Risk for surgical staff to contaminate the outside surface of the surgical clothing system during visit in uncontrolled environment outside the surgical department. The level of the §-contamination on the surface depends on type of environment and the exposure time.
- Changing procedure needs to be reviewed and it could be appropriate for personnel to change their surgical clothing to a new set after visits to uncontrolled areas outside the surgical department or even change to a new set for each infection prone surgery. Local changing rooms close to the ultraclean air operating rooms should be considered.

Evaluation of clothing systems

- The source strength of surgical clothing system during ongoing surgery depends on the fabric, the design, and the activity level of the personnel.
- Surgical clothing system of mixed material the source strength value is 4.2 CFU/s during high activity and 1.8 CFU/s during low staff activity.
- Olefin clothing system without and with knee length boots and the activity is mainly high, the source strength is 1.2 CFU/s and 0.4 CFU/s respectively.
- Knee length boots reduce the number of airborne bacteria-carrying particles (CFU/m^3).

Tissue and cells establishments

- Lack of knowledge and understanding of contamination control cause non-compliance of today´s cleanliness requirements according to EUTCD.
- Most of the operating rooms classified as tissue and cell establishment, did not fulfill the recommendation of airborne microbial cleanliness in ultraclean air operating rooms according to SIS-TS 39:2015 (2015) of maximum 10 CFU/m^3.
- Working, cleaning and maintenance procedures need to be established or improved.
- Local UDF units for handling of tissue and cells should be considered.

Door openings (theoretical aspects)

- The calculation showed the necessity to eliminate, or at least reduce, door openings between the operating room and the adjacent room during ongoing infection prone surgery.
- If door openings are needed during ongoing surgeries, the inflow of airborne microorganisms from adjacent rooms into the operating room can be reduced by:
    - Minimize the temperature difference between the operating room and the adjacent rooms
    - Minimize the door opening time
    - Decreasing the door opening by designing door sizes for its correct use (only have larger door openings where transportation of materials and patients will be performed)
    - Control the cleanliness in the adjacent rooms or use airlocks

12.3 Future Studies

Further studies could preferably focus on the following:

- Study in detail the logistic procedures of materials (sterilized instruments/equipment and used instruments) between the sterile supply center and the operating department including storage within the sterile supply center and the operating department. Perform risk assessment to identify risks and improvements with focus on contamination control.
- Process development to increase contamination control during transport of sterile reusable instruments and equipment from the sterile supply center to the operating department.
- Investigate the risk of microbiological contaminants from the surface of surgical clothing system to the surroundings (operating rooms and other areas within the operating department).
- Improve the design of airlocks/changing rooms for personnel including storage of surgical clothing system to avoid contamination during storage and change of clothing.
- Increase the understanding and knowledge of contamination control and current cleanliness requirements within hospitals.
- Perform a GAP-analysis to decrease the difference between the pharmaceutical industry and tissue and cells establishment with focus on GMP requirement for premises.
- A team research effort in the ultraclean operating departments among architects, cleanroom experts and the healthcare.

REFERENCES

Abel, E., Allander, C., (1966), Investigation of a new air distribution system for clean rooms, VVS, No 8 (in Swedish).

Allander, C., (1965), Ventilation in rooms with extreme cleanliness requirements, VVS, No 4 (in Swedish).

Bird, R.B., Stewart, W.E., Lightfoot, E.N., (1960), Transport Phenomena. John Wiley & Sons, Inc., New York.

Blomqvist, C. (2009) Distribution of Ventilation Air and Heat by Buoyancy Forces Inside Buildings, PhD. Thesis, Centre of Built Environment, University of Gävle and KTH.

Blowers, R., Crew, B., (1960), Ventilation of operating theatres, J. Hyg. Camb., 58, 427-448.

Bourdillon, R. B., Lidwell, O. M., Lovelock, J. E., et al (1948), Studies in Air Hygiene, Medical Research Council special report series No 262, His Majesty´s Stationary Office, London.

Charnley, J., (1964), A sterile-air operating theatre enclosure, Brit. J. Surg., 51, No 3, March 195-205.

Charnley, J., (1972), Postoperative infection after total hip replacement with special reference to air contamination in the operating room, Clin Orthop Relat Res, no 87, 167-187.

Charnley, J., Eftekhar, N., (1969), Postoperative infections in total prosthetic replacement arthroplasty of hip joint, Brit. J. Surg., 56, No 9, September, 641-649.

EN 13795-2:2019, (2019), Surgical clothing and drapes – Requirements and test methods – Part 2: Clean air suits, European Committee for Standardization, Brussels.

Etheridge, D., Sandberg, M. (1996) Building Ventilation. Theory and Measurement. John Wiley & Sons Ltd., Chichester.

EU GMP (1997 revised 2003, 2008), European Commission. The Rules Governing Medicinal Products in the European Community, Vol. IV. EU Guide to Good Manufacturing Practice, Annex 1, Manufacture of Sterile Medicinal Products.

European Union (2004), Directive 2004/23/EC of the European Parliament and of the Council of 31 March 2004 on setting standards of quality and safety for the donation, procurement, testing, processing, preservation, storage and distribution of human tissues and cells, Official Journal of the European Union.

European Union (2006), Commission Directive 2006/86/EC of 24 October 2006 implementing Directive 2004/23/EC of the European Parliament and of the Council as regards traceability requirements, notification of serious adverse reactions and events and certain technical requirements for the coding, processing, preservation, storage and distribution of human tissues and cells. Official Journal of the European Union.

European Union (2006), Commission Directive 2006/17/EC of 8 February 2006 implementing Directive 2004/23/EC of the European Parliament and of the Council as regards certain technical requirements for donation, procurement and testing of human tissues and cells. Official Journal of the European Union.

European Union (2012), Commission Directive 2012/39/EU of 26 November 2012 amending Directive 2006/17/EC as regards certain technical requirements for the testing of human tissues and cells. Official Journal of the European Union.

Friberg, B., (1998), Aerobiology in the operating room and its implications for working standards, Umeå University Medical Dissertations, New Series no 556-ISSN 0346-6612, ISBN 91-7191-506-0.

Fritzsche, C., Lilienblum, W. (1968) Neue Messungen zur Bestimmung der Kälteverluste an Kühlrahmtüren, Kältetechnik – Klimatisierung, Vol. 20. 9; 279-286.

Fuchs, N.A., (1964), The Mechanics of Aerosols, Pergamon Press, Oxford.

Hinze, J.O., (1975), Turbulence, McGraw-Hill, Inc., New York.

Howorth, F. H., (1980), Airflow patterns in the operating theatre: A paper read at R. C. S. Symposium, Engineering of Medicine, 9, No 2, 87-92.

Howorth, F. H., (1984), The design and utilization of operating theatres, R. C. S., Book 39-60, Edward Arnold, London.

Howorth, F. H., (1985), Prevention of Airborne Infection during Surgery, Ashrae Transactions, 91, Pt 1, 291-304.

Institute of Environmental Sciences and Technology (2011), IEST-RP-CC003.4, Garment System Considerations for Cleanrooms and Other Controlled Environments, Arlington Heights, IL, USA.

Isfält, E., Ljungqvist, B., and Reinmüller, B. (1996), Simulation of Airflows and Dispersion of Contaminants Through Doorways in a Suite of Cleanrooms, European Journal of Parental Sciences, Vol. 1:3, 67-73.

ISO 14644-3, (2005), Cleanrooms and associated controlled environments – Part 3 Test methods, International Organization for Standardization, Geneva.

Jordestedt, M. (2015), Microbiological Contamination of a Surgical Clothing System – A measurement Study of the Number of CFU on the Surface of a Surgical Clothing System after Exposure in an Uncontrolled Environment, Master Thesis E2015:12, Building Services Engineering, Chalmers University of Technology, Gothenburg, Sweden.

Kasina, P., Tammelin, A., Blomfeldt (2016), A-M., et al, Comparison of three distinct clean air suits to decrease the bacterial load in the operating room: an observational study, Patient Safety in Surgery, 10:1

Kiel, D. E., Wilson, D. J. (1989), Combining Door Swing Pumping with Density Driven Flow, ASHRAE Transactions, 95, Part 2.

Lag 2008:286 om kvalitets- och säkerhetsnormer vid hantering av mänskliga vävnader och celler.

Lidwell, O. M., Lowbury, E. J. L., Whyte, W., Blowers, R., Stanley, S. J., Lowe, D., (1982), Effect of ultraclean air in operating rooms on deep sepsis in the joint after total hip or knee replacement: a randomized study, Brit. Medical Journal, 285, 10-14.

Ljungqvist, B., (1979), Some observations on the interaction between air movements and the dispersion of pollution, Document D8:1979, Swedish Council for Building Research, Stockholm.

Ljungqvist B. and Reinmüller, B. (1993), Interaction Between Air Movements and the Dispersion of Contaminants: Clean Zones with Unidirectional Air Flow. Journal of Parenteral Science and Technology, Vol.47: 60-69.

Ljungqvist B., and Reinmüller, B. (1995), Hazard Analyses of Airborne Contamination in Clean Rooms – Application of Method for Limitation of Risks. PDA Journal of Pharmaceutical Science and Technology, Vol. 49: 239-243.

Ljungqvist B., and Reinmüller, B. (1997), (reprint 2002), Clean Room Design, Minimizing Contamination Through Proper Design, Interpharm CRC Press LLC, Boca Raton, FL.

Ljungqvist B., and Reinmüller, B. (1998a), Design of HEPA-filters Above Autoclaves and Freeze-Dryers, PDA Journal of Pharmaceutical Science and Technology, Vol. 52: 340-343.

Ljungqvist, B., and Reinmüller, B. (1998b), Active Sampling of Airborne Viable Particles in Controlled Environments; a comparative study of common instruments, European Journal of Parenteral Sciences, 3(3), 59-62

Ljungqvist B., and Reinmüller, B. (2004), Cleanroom Clothing Systems: People as a Contamination Source. PDA/DHI Publishing LLC, River Grove, IL, USA,ISBN 1-930114-60-5.

Ljungqvist B., and Reinmüller, B. (2006), Practical Safety Ventilation in Pharmaceutical and Biotech Cleanrooms, PDA, Bethesda, MD, DHI Publishing LLC, River Grove, IL, USA.

Ljungqvist, B., and Reinmüller, B. (2008), Monitoring efficiency of microbiological impaction air samplers, European Journal of Parenteral & Pharmaceutical Sciences, 13(4), 93-97.

Ljungqvist, B., and Reinmüller, B., Eds, (2013), Practical Safety Ventilation in Operating Rooms – An Introduction, Report No D2013:02, Building Services Engineering, Chalmers University of Technology, Göteborg.

Ljungqvist, B., Reinmüller, B. (2014), Clothing systems evaluated in a dispersal chamber, European Journal of Parenteral & Pharmaceutical Sciences, 19 (2), 67-69.

Ljungqvist, B., Reinmüller, B., Gustén, J., Gustén, L., Nordenadler, J. (2009), Contamination risks due to door openings in operating rooms, European Journal of Parenteral & Pharmaceutical Sciences, 14(4), 97-101.

Ljungqvist, B., Reinmüller, B., Gustén, J., Nordenadler, J., (2014), Performance of clothing systems in the context of operating rooms, European Journal of Parenteral & Pharmaceutical Sciences, 19 (3), 95-101.

Ljungqvist, B., Reinmüller, B., Tammelin A., (2012), Comparison between two measuring methods with active sampling of airborne viable particles, European Journal of Parenteral & Pharmaceutical Sciences, 17 (2), 56-59.

LVFS 2008:12 Läkemedelsverkets föreskrifter om hantering av mänskliga vävnader och celler avsedda för läkemedelstillverkning.

LVFS 2011:3 Läkemedelsverkets föreskrifter om läkemedel som omfattas av sjukhusundantaget.

Nordenadler, J., (2010), Some observations on safety ventilation in operating rooms, Ph.D. thesis, Bulletin No 74, Building Services Engineering, KTH, Stockholm, (in Swedish).

Reinmüller, B., (2001), Dispersion and Risk Assessment of Airborne Contaminants in Pharmaceutical Clean Rooms, PhD-thesis, Bulletin No 56, Building Services Engineering, KTH, Stockholm.

Reinmüller, B., and Ljungqvist B., (2000), Evaluation of cleanroom garments in a dispersal chamber – some observations. European Journal of Parenteral Sciences, 5(3):55-58.

Reinmüller, B., and Ljungqvist B., (2003), Modern cleanroom clothing systems: people as a contamination source. PDA Journal of Pharmaceutical Science and Technology, 57(2):114-125.

Romano, F., Gusten, J., Joppolo, C., Ljungqvist, B., Reinmüller, B. (2015), Some aspects on sampling efficiency of microbial impaction air samplers, Particuology, 20, 110-113.

Romano, F., Ljungqvist, B., Reinmüller, B., et al,(2016), Dispersal chambers used for evaluation of cleanroom and surgical clothing systems – examples of performed tests and results. International Symposium of Contamination Control (ICCCS*)*, Sao Paulo, Brazil.

Schulz, L. (2001) Secondary Safety-Barrier Performance in Laboratory Ventilation, An Experimental Study, Lic. Thesis, Document D:60:2001, Building Services Engineering, Chalmers University of Technology (in Swedish).

Shaw, B. H., and Whyte, W. (1974), Air Movement Through Doorways –The Influence of Temperature and its Control by Forced Airflow, Building Services Engineering, Vol. 42: 210-218.

SIS-TS39:2015 (2015), Microbiological cleanliness in the operating room – Preventing airborne contamination – Guidance and fundamental requirements, SIS Swedish Standards Institute.

Socialstyrelsen (2009), SOSFS 2009:31 (M) Föreskrifter, Vävnadsinrättningar i hälso- och sjukvården m.m., Socialstyrelsens författningssamling.

SOSFS 2008:30 Socialstyrelsens föreskrifter om donation och tillvaratagande av vävnader och celler.

SOSFS 2009:31 Socialstyrelsens föreskrifter om vävnadsinrättningar i hälso- och sjukvården m.m.

SOSFS 2009:32 Socialstyrelsens föreskrifter och allmänna råd om användning av vävnader och celler i hälso- och sjukvården och vid klinisk forskning.

SS 8760015:2017 Basic requirements for transportation, storage and handling of sterile medical devices intended to be used within health care.

Tammelin, A., Ljungqvist, B., Reinmüller, B. (2012), Comparison of three distinct surgical clothing systems for protection from air-borne bacteria: A prospective observational study, Patient Safety in Surgery, 6:23.

Tammelin, A., Ljungqvist, B., Reinmüller, B. (2013), Single-use surgical clothing system for reduction of airborne bacteria in the operating room, *Journal of Hospital Infection*, 84, 245-247.

Ullmann, C., (2011), Airborne Contamination Risks in Autoclaves and Freeze-Dryers when Chamber Doors are open, Lic thesis, Bulletin No 76, Building Services Engineering, KTH, Stockholm.

Ullmann, C., Ljungqvist, B., Reinmüller, B., (2017a), Microbial contamination risks of the surface of surgical clothing systems – an observational study, European Journal of Parenteral & Pharmaceutical Sciences, 22(1); 6-12.

Ullmann, C., Ljungqvist, B., Reinmüller, B., (2017b), Some aspects of protective efficacy of surgical clothing systems concerning airborne microorganisms based on results from measurements in a dispersal chamber and during surgical procedures, European Journal of Parenteral & Pharmaceutical Sciences, 22 (2):51-58.

Whitfield, W. J., (1967), Microbiological Studies of Laminar Flow Rooms, Bull. Parenteral Drug Assoc., 21(2), 37-45.

Whyte, W., (1986), Sterility Assurance and Models for Assessing Airborne Bacterial Contamination, Journal of Parenteral Science and Technology, Vol. 40: 188-197.

Whyte, W., (1999), Cleanroom Design, Second Edition, Johan Wiley & Sons, Ltd, Chichester.

Whyte, W., (2001), Cleanroom Technology, Fundamentals of Design, Testing and Operation, Johan Wiley & Sons, Ltd, Chichester.

Whyte, W., Hamblen, D.L., Kelly, I.G., Hambraeus, A., Laurell, G., (1990), An investigation of occlusive polyester surgical clothing, J. Hosp Inf., pp. 363-374.

Whyte, W., Hejab, M. (2007), Particle and microbial airborne dispersion from people, European Journal of Parenteral & Pharmaceutical Sciences, 12 (2), 39-46.

Whyte, W., Lidwell, O. M., Lowbury, E. J. L., Blowers, R., (1983), Suggested bacteriological standards for air in ultraclean operating rooms, Journal of Hospital Infection, 4, 133-139.

Whyte, W., Shaw, B. H., Barnes, R., (1973), A bacteriological evaluation of laminar-flow system for orthopaedic surgery, J. Hyg. Camb., 71, 559-564.

Williams, R. E. O., Blowers, R., Garrod, L. P., Shooter, R. A., (1960), Hospital Infection, Causes and Preventions, Lloyd-Luke (Medical Books) LTD, London (second edition, 1966).

Wilson, D.J., Kiel, D.E. (1990), Gravity Driven Counter flow Through an Open Door in a Sealed Room, Building and Environment, Vol. 25:4; 379-388.

APPENDIX

A1 – Ullmann, C., Ljungqvist B., Reinmüller B., (2010), Design of HEPA-filter units in order to prevent airborne contamination of autoclaves and freeze dryers when doors are open, European Journal of Parenteral & Pharmaceutical Sciences, Vol. 15, No 2, pp. 53-59

A2 –Ullmann, C., Ljungqvist B., Reinmüller B., Sahlén J., (2012) Study of proper placements of HEPA-filter units in order to prevent airborne contamination of autoclaves in aseptic production by using computational fluid dynamics, European Journal of Parenteral & Pharmaceutical Sciences, Vol. 17, No 4, pp. 148-156

A3 – Ullmann, C., Ljungqvist B., Reinmüller B., (2015), Requirements and environmental monitoring in pharmaceutical production versus operating rooms in hospitals with focus on airborne particles and microorganisms, European Journal of Parenteral & Pharmaceutical Sciences, Vol. 20, No 3, pp. 100-103

A4 –Ullmann, C., Ljungqvist B., Reinmüller B., (2017), Microbial contamination risks of the surface of surgical clothing systems – an observational study, European Journal of Parenteral & Pharmaceutical Sciences, Vol. 22, No 1, pp. 6-12

A5 –Ullmann, C., Ljungqvist B., Reinmüller B., (2017), Some aspects of protective efficacy of surgical clothing systems concerning airborne microorganisms based on results from measurements in a dispersal chamber and during surgical procedures, European Journal of Parenteral & Pharmaceutical Sciences, Vol. 22, No 2, pp. 51-58